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S-Cam Brake Effectiveness Comparison Using Two Fixtures and Two Lining Types on a Single Inertia Dynamometer

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16. Abstract

There are currently no Federal performance standards for either original equipment or replacement brake linings for air-braked vehicles. NHTSA has been petitioned to institute such a standard. An integral part of a brake lining performance standard would be a procedure for determining lining performance. This report documents the results of NHTSA research to examine the variability present in the Society of Automotive Engineers (SAE) recommended practice J1802 Brake Block Effectiveness Rating.

For this research, four SAE J1802 brake test fixtures were obtained from government and industry testing laboratories. Physical measurements were made on three of the major fixture components: the s-cams, the spiders, and the rotochambers, in an attempt to identify geometric variations between the fixtures. The spiders were measured at a precision machine shop for hole alignment and planarity. The s-cams were measured for lobe rise with respect to input shaft rotation angle. The rotochambers were calibrated for linearity in output force versus displacement and pressure.

Two fixtures were then tested on a brake dynamometer. Each fixture was tested with two sets each of two types of brake lining blocks. A single operator performed the tests on a single dynamometer to reduce the number of sources of variability.

The variability in brake effectiveness values found in this study was considerably smaller than that found during a previous round-robin test series that used multiple operators running multiple dynamometers. The geometric variances found from the physical measurements probably contributed only a negligible amount to the total variability of the effectiveness values measured during the dynamometer tests. While only a very limited number of tests were performed, the results suggest that much of the variability found in the past round-robin testing may have come from sources other than the test fixtures (dynamometer, operator, slightly different set-up procedures, brake lining and/or brake drum material differences, etc.).

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
deg F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	deg C

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
deg C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	deg F

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ACKNOWLEDGMENTS

The testing program documented in this report was a coordinated effort by the National Highway Traffic Safety Administration (NHTSA) Vehicle Research and Test Center (VRTC), the Transportation Research Center Inc. (TRC), and the Heavy Duty Brake Manufacturers= Council (HDBMC) to evaluate the sensitivity of operator, fixture, and dynamometer variability in determining the effectiveness rating of brake linings.

The authors wish to recognize the outstanding support of our research colleagues. Jim Preston was outstanding in coordinating the logistics of all the components and test fixtures, while preparing for and performing the tests, and compiling the hundreds of measurements from the devices. Don Thompson was instrumental in preparing the data acquisition system, setting up the Abex cam torque sensor, and providing the instrumentation calibrations. Leslie Portwood persevered through countless adjustments in tabulating the extensive groups of measurements and graphs.

The effort of Jim Britell from NHTSA Research and Development greatly aided in the liaison and completion of the study.

A special thank you to Jim Lawrence of the Heavy Duty Brake Manufacturers= Council for his earnest support and coordination on behalf of the fixture and lining suppliers, and to our suppliers: BrakePro Ltd., Carlisle Motion Control Products, Cooper/Abex Friction Products, Haldex-Midland Friction Materials Research and Development Center and Link Engineering, and technical support groups: Allied Signal (Bendix), Greening Associates, Inc., Ometek, Inc., and Meritor (Rockwell).

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J. Gavin Howe

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TABLE OF CONTENTS

Section **Page**

TABLE OF CONTENTS (continued)

Section **Page**

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF TABLES

Department of Transportation
National Highway Traffic Safety Administration
Vehicle Research and Test Center

TECHNICAL SUMMARY

Report Title: S-Cam Brake Effectiveness Comparison Using Two Fixtures and Two Lining Types on a Single Inertia Dynamometer	Date: September 2000
Report Author(s): Richard L. Hoover, J. Gavin Howe, Mark A. Flick, and David A. Dashner	

The minimum braking performance of a new heavy vehicle is specified by the U.S. Government in Federal Motor Vehicle Safety Standard (FMVSS) No. 121. However, there currently are no Federal standards for the performance of either original equipment or replacement brake linings for air-braked vehicles.

In 1987, the American Trucking Association (ATA) petitioned the National Highway Traffic Safety Administration (NHTSA) to develop replacement brake lining standards for heavy vehicles. Such a standard would include a procedure to measure brake lining performance ratings that were representative of brake performance on actual vehicles.

NHTSA has run several developmental programs in an attempt to develop a repeatable procedure that would produce the required lining performance ratings. An initial round-robin study involved the NHTSA=s Vehicle Research and Test Center (VRTC) and numerous industry laboratories performing the Society of Automotive Engineers (SAE) J1802 ABrake Block Effectiveness Rating@ procedure on one brake assembly and one fixture on the various dynamometers. The results from the single fixture tests showed good agreement among the different dynamometers using one fixture, a single set of linings, and one brake drum. This indicated that all of the laboratories were using the same parameters and were calculating the effectiveness values the same way. With such close agreement, the laboratories were now ready to run similar Astandard@ brakes on their individual dynamometers and correlate the results.

The second round-robin comparison was conducted where each of the laboratories independently performed J1802-type tests using similar brake components and similar fixtures, but on different dynamometers. The results showed significant differences in test results for a given lining material tested at different sites.

Since there was no immediate answer as to why the large variation in ratings between the laboratories using different brakes, but close correlation using the same brake, NHTSA opted to develop a new procedure, that was modified version of SAE J1802, in an effort to identify a procedural cause to the high variability. The development team explored variations in burnish cycles, number of effectiveness stops, and pre-cutting profiles. Even after making some improvements, the procedure still showed considerable variation in lining effectiveness ratings upon testing several groups of blocks from one batch of linings.

After extensively reviewing the results from the previous programs, the current program=s goals were developed. In an attempt to reduce the number of variables affecting the measured performance ratings, NHTSA requested that the available fixtures from brake component manufacturers be tested at the VRTC on a single dynamometer. Four fixtures were made available for evaluation. These fixtures were disassembled and several components physically measured. The component parameters inspected were the spider dimensions, the chamber force versus pushrod extension characteristics, and the s-cam lobe rise versus input shaft rotation angle. It was thought that if there were large tolerance differences between the various components, this might explain some of the large variations seen in the second round-robin. One operator set up and performed the tests. Two types of linings were tested: a regular lining and a softer one. The linings were mounted on cast shoes to minimize compliance of the brake shoe. The linings were machine cut to the J1802 radius to reduce the number of conditioning cycles required to achieve full lining surface contact with the drum. Direct comparative tests were performed on two fixtures using the conditioned linings.

The spider dimensions, the chamber force curves and the s-cam curves showed close agreement from fixture-to-fixture. The small physical differences that were seen between the fixtures should have only a minimal effect on the total variability of lining performance ratings.

The dynamometer fixture comparison tests produced results ranging from 1.3 to 10.2 percent difference for one set of linings on two different fixtures, (similar to the results of the first round-robin test series). In comparison, data from different, but supposedly identical (same production batch), linings from one supplier tested on one fixture resulted in 2.5 to 16.9 percent differences. These results suggest that even under the best test conditions (one test site, one dynamometer, one dynamometer operator, one test fixture) that the amount of variability in different brake lining material/drum material from the same manufacturer(s) and the same batch can be relatively high. When other potential sources of variability are considered (different test fixtures, different dynamometers, different dynamometer operators, etc.) the potential amount of variability may be greater than what would be acceptable for development of a Federal Motor Vehicle Safety Standard to rate brake linings.

In summary, the test matrix was designed to reduce the variability in test results due to dynamometer, operator, and set-up procedure differences and other unforeseen potential sources. Having a single operator perform testing with a single dynamometer using two different test fixtures produced results that had far less variability than those found where multiple laboratories performed the tests. While only a very limited number of tests were performed, the results suggest that much of the variability found during the second round-robin came from sources other than the test fixtures (dynamometer, operator, slightly different set-up procedures, brake lining and/or brake drum material differences, etc.).

1.0 INTRODUCTION

1.1 Purpose of This Study

The minimum braking performance of a new vehicle is specified by the U.S. Government in either Federal Motor Vehicle Safety Standard (FMVSS) 105 or 135 for hydraulically braked vehicles or in FMVSS 121 for air-braked vehicles. Currently, however, there are no Federal standards for the performance of either original equipment or replacement brake linings. This is of particular concern in the area of replacement brake linings, where linings may be purchased and installed on a vehicle which significantly affect the braking performance of the vehicle. In 1969, the National Highway Traffic Safety Administration (NHTSA) recognized the need for a brake lining standard when it issued Docket 1-4 which said: "The Administrator is considering the issuance of a federal motor vehicle safety standard ... specifying performance requirements ... for brake linings ... ."

The purpose of this study is to examine the SAE Recommended Practice J1802 "Brake Block Effectiveness Rating" [1] as a possible brake lining performance rating tool for air-braked vehicles. In particular, four test fixtures were brought to NHTSA's Vehicle Research and Test Center (VRTC) to examine dimensional tolerance differences. Two of these fixtures were then selected to be used to perform SAE J1802 tests on several brake lining materials to see how much variability there was in the measured brake effectiveness values. A single operator performed the tests on a single dynamometer to reduce the number of potential sources of variability.

1.2 Background

Several states require brake linings to be rated and labeled using the SAE Recommended Practice J661, "Brake Lining Quality Control Test Procedure," [2]. The SAE J661 (adopted in 1958) procedure measures the friction of a one inch square piece of the material against a relatively small drum to rate the material. J661 was developed for quality control purposes. It was not intended to rate linings, but since it was the only method available, it was adopted by some states as a requirement for brake lining rating. Due to the size of the specimen (1-inch x 1-inch) and to the diameter of the drum (11-inch) used, these ratings are not representative of the performance of the material in a full scale brake. Previous NHTSA testing [3,4] and testing by other organizations has shown that linings having the same SAE J661 rating installed on passenger cars can produce significantly different vehicle performance. Inertia brake dynamometer testing has also shown significant differences in lining performance for heavy vehicle brake linings with the same SAE J661 rating.

In 1986, development of a new SAE procedure, which was to be a more realistic measure of the performance of lining material in an air brake, was initiated. This procedure has since been finalized and is SAE Recommended Practice J1802, "Brake Block Effectiveness Rating." The SAE J1802 procedure uses a full scale brake tested on an inertia dynamometer to give two rating numbers which characterize the effectiveness of the lining at low (normal) and high temperatures. Along with the J1802 procedure, the SAE committee developed a lining marking procedure, SAE J1801, "Brake Effectiveness Marking for Brake Blocks," [5] which describes a method for permanently marking the linings with the ratings determined by testing to SAE J1802.

In 1987, the American Trucking Association (ATA) petitioned NHTSA to develop replacement brake lining standards for heavy vehicles. For heavy vehicle fleets to ensure that replacement linings installed on their vehicles give adequate braking performance, the ATA petition requested standards be developed and adopted which would give brake lining performance ratings which are representative of brake performance on the vehicle. These ratings could then be used to select replacement linings having appropriate performance levels. This petition was granted and is, as of May 2000, an open rulemaking issue.

The current brake fixture used for the J1802 procedure includes all of the brake components of a standard brake between the axle and the wheel. The parts selected for this fixture are all standard "off-the-shelf" parts with the exception of the cam, which has a profile that was developed by making a composite of the profiles of cams available on the market. Cams used with the J1802 fixture must be machined to that specific profile and hardened. The brake shoes used in the

J1802 fixture are off-the-shelf items but are made of cast iron, whereas most over-the-road trucks use fabricated steel brake shoes.

In addition to the parts included in the brake fixture, SAE J1802 includes a specification for grinding the linings after they are installed on the shoes. This was done to improve the fit of the lining to the brake drum with the idea that this would improve the consistency of the results from one test to another. Such grinding is not, however, a common procedure, and different test labs use different methods to accomplish this procedure.

Initial testing to the SAE J1802 procedure showed significant differences in test results for a given lining material tested at multiple test sites. This prompted a round-robin set of tests where a single fixture, one set of linings, and one drum were passed to different test sites and a very simplified test sequence was performed (by contrast, a typical test is run with a new set of linings and a new drum for each test). Prior to starting the round-robin tests, the linings on this fixture were burnished and tested multiple times to stabilize their output to minimize the confounding effect of brake conditioning in differences seen between test labs. Once this stabilization process was complete, the brake assembly was shipped as a unit, without disassembly, from one site to the next, installed on the dynamometer and tested. The simplified procedure used for this round-robin test consisted of a short burnish and then ten constant pressure stops at a range of pressures. The lining effectiveness was determined from the ten constant pressure stops at each test site by calculating the slope of a line fit through the output torque versus the input torque (brake chamber force times slack adjuster length) data. The calculated brake effectiveness results for each of the test sites participating in the single fixture round-robin are shown in Figure 1.1.

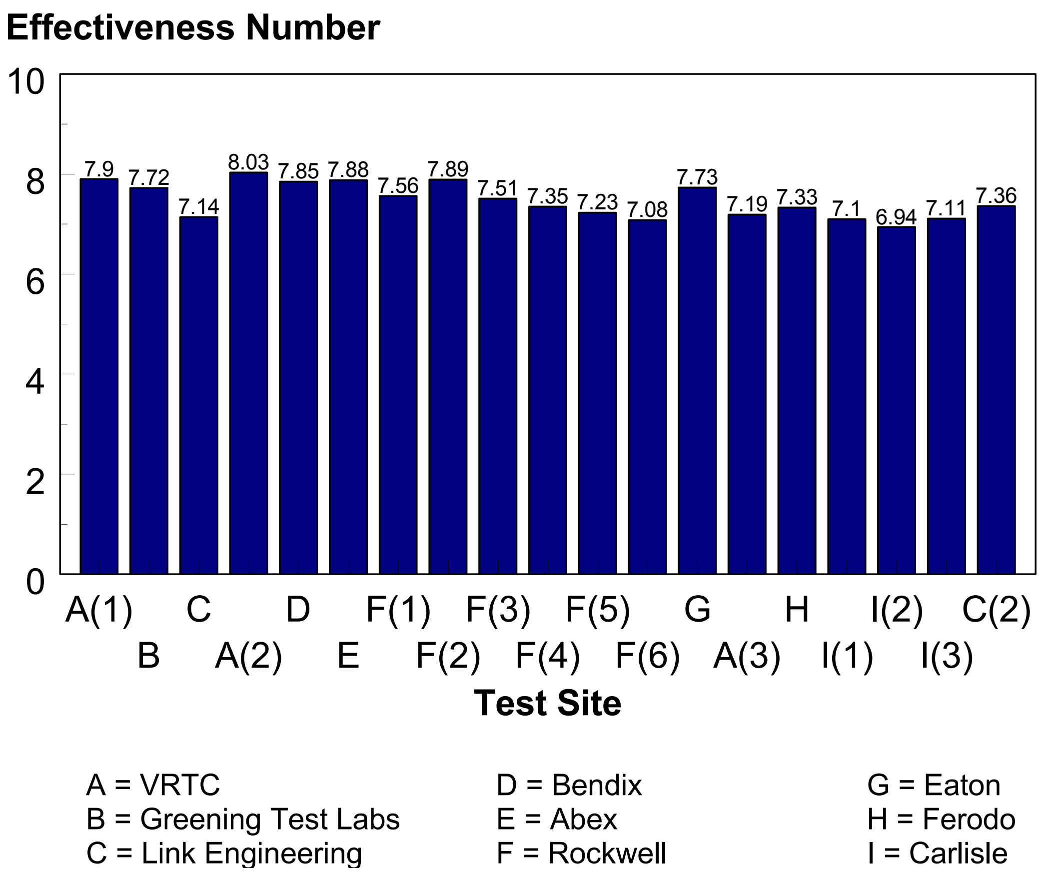


FIGURE 1.1 – Brake Effectiveness Results for Single Fixture Round-Robin

In general, the results from the single fixture round-robin showed good agreement among different dynamometers using one fixture, a single set of linings, and one brake drum. While there were differences in the effectiveness numbers measured at the different sites, these differences were small and were, in part, due to changes occurring in the brake lining from conditioning. These conditioning changes can be seen by noting the differences in the results from the repeatability tests at site F.

Based on the results of the round-robin using a single fixture, which showed generally good agreement among the dynamometers at various test sites, a second round-robin was initiated. This second round-robin was to compare results of tests at various test sites with the various labs using different test fixtures and a new set of linings and a new drum for each test. Three lining materials were chosen to be tested at each of the sites, with all of the sets of linings for a given lining material taken from a single production batch. (Brake lining effectiveness is known to be somewhat variable from set to set due to the manufacturing process. It was hoped that getting linings from a single production batch would minimize this variability which would confound the differences seen among results from the various test sites.) The three materials chosen were known to have distinctively different friction levels, high - medium - and low. Additionally, a large quantity of drums were purchased to be distributed with the linings so all of the drums would also be from a single batch.

The procedure used for the round-robin using different fixtures and different materials was the version of the J1802 procedure that was current at the time the testing was started. (A number of changes have been made to the procedure over the past several years.) The procedure included a "normal" temperature section and a high temperature section. Each section had a 200 stop burnish followed by a series of nine constant pressure stops at pressures ranging from 10 to 50 psi in 5 psi steps. An effectiveness rating was determined by calculating the slope of a linear fit of the output torque versus the input torque for the nine constant pressure stops in the normal temperature and the high temperature effectiveness sections. The results were reported as a normal temperature and a high temperature effectiveness rating.

Seven test labs participated in this round-robin series. At some of the test sites, three sets of linings and drums were tested for each of the three lining materials. At other test sites, only one set of linings and drums were tested for each of the three materials. The effectiveness ratings measured for these tests are shown in Figure 1.2. The results are grouped by the three lining materials tested and by each test site within each group of materials. These results show substantial differences in the results among the various participating labs, particularly for the high friction material (Abex 1083-49). Also note that the differences among the test sites for the two lower friction materials are larger than the differences between the two material's friction levels.

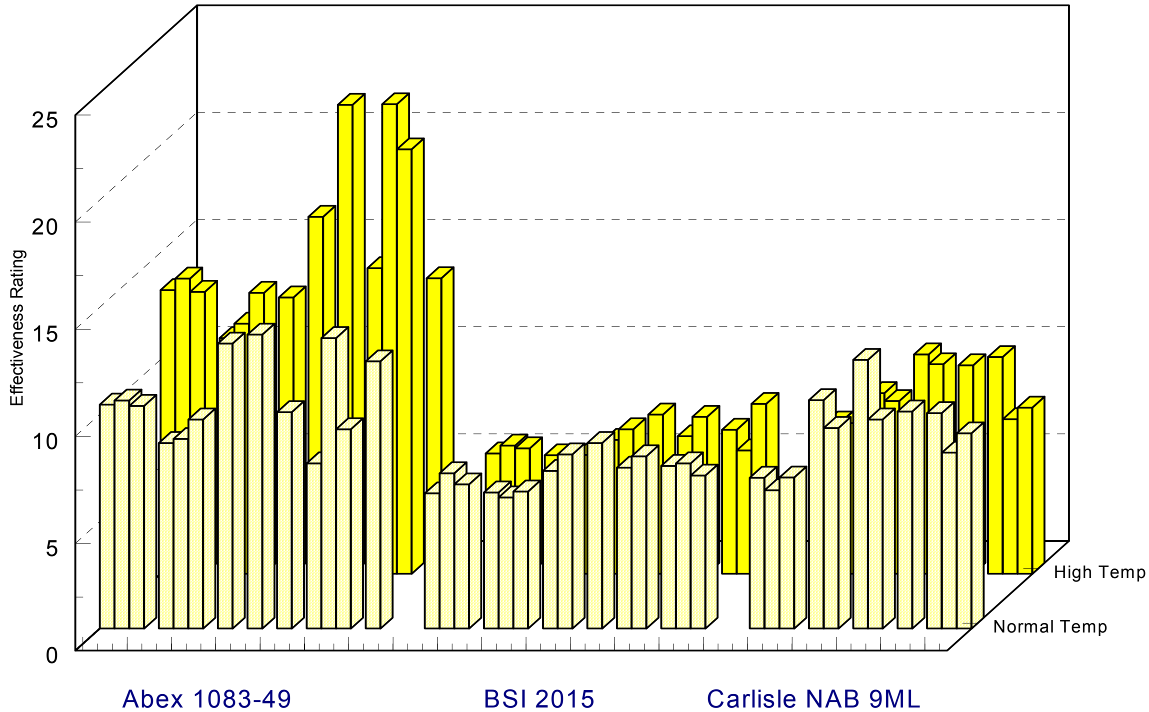


FIGURE 1.2 – Brake Effectiveness Ratings for Round-Robin Using Different Fixtures

Subsequent to the round-robin tests, additional tests were conducted in an attempt to determine the cause of the differences among the test sites. These tests focused primarily on the grinding technique and the level of burnishing performed prior to measuring effectiveness. These additional tests failed to resolve the lab-to-lab differences.

The American Trucking Association's, The Maintenance Council (TMC), concerned with the slow progress of SAE J1802, developed a recommended practice for replacement brake linings which was issued in 1995. This recommended practice, RP 628, "Aftermarket Brake Lining Classification," [6] was intended to be an interim measure to be used until the SAE J1802 was completed and refined. RP 628 is conducted using an inertia brake dynamometer with linings installed on one of two off-the-shelf brakes. The procedure used is the FMVSS 121D [7] dynamometer procedure.

The RP 628 tests are conducted by "qualified" test labs. The SAE has formed a committee, the Brake Lining Performance Review Committee, which is responsible for determining which test labs are qualified to conduct the test and to review the results to determine which lining materials are qualified. For a lining material to be qualified, it must meet all of the conditions of the FMVSS 121 brake dynamometer test. A list is published periodically indicating which linings are qualified. Additionally, the torque measured during a specified 40 psi constant pressure stop in the test is also listed to allow some comparison of the effectiveness for different brake linings.

As was noted above, the RP 628 procedure was intended to be an interim measure as it was recognized that the procedure had a number of shortcomings. The allowance of two possible brakes to be used to conduct the test can result in two different determinations for a given material. Also, the FMVSS 121 dynamometer procedure has a number of sections which do not have very exact test specifications, which again allows for possible differences in results, depending upon the exact procedure followed. Finally, the publishing of a torque value for a single stop may not be a reliable method of ensuring replacement linings will have lining effectiveness levels similar to those of the original equipment linings.

Given the difficulties in producing results which were in agreement among the various labs using SAE J1802, declining interest within the brake lining industry to further refine the J1802 concept, and ATA's continued requests for a federal standard, NHTSA's Office of Crash Avoidance Standards decided to attempt to develop a fixture and a test procedure within NHTSA. Some limited number of tests were to be run using the NHTSA developed fixture and procedure, and the level of industry acceptance would be assessed.

For the NHTSA fixture, an off-the-shelf brake was used. The most common brake in this size was selected, the Rockwell Q-Plus brake. Two changes were made to the initial lining preparation. First, the grinding process was replaced by a lathe cut rather than using a lining grinding tool as was typically done for the J1802 tests. Second, a different grind/lathe cut profile was used. These changes were made as a result of the tests conducted on the J1802 fixture in the attempt to determine the cause of differences seen in the round-robin tests.

Changes in the drum temperature control technique included averaging the output of a nine thermocouple array, that was welded to the surface of the drum, rather than using a single thermocouple imbedded in the drum as specified in J1802. This array provided a more representative bulk temperature than the single hole location measuring technique. The single hole technique previously was found to clog with debris and indicate sporadic high and low values when compared to the array technique, and the array was less likely to break (or pop out of the hole) if the drum wore a little too much during extended testing.

The test procedure used was a modified SAE J1802 procedure. The major modifications were to the burnish and the number of stops made during the effectiveness portions of the test. The burnish was conducted making stops at 6 ft/sec^2, rather than the 10 ft/sec^2 specified in J1802, to better represent "real world use". To compensate for this change, however, the number of burnish stops was increased from 200 to 400 in the normal temperature burnish. The number of stops in the effectiveness test was increased from 9 to 18. The pressures used for the effectiveness test were the same as those in J1802; an additional stop at each pressure was added to give additional data to be used in calculating the fit of input versus output torques.

Some preliminary tests were conducted to ensure the practicability of the procedure after these changes. Ten repeat tests were conducted on a single lining material from a single production batch. These results are shown in Figure 1.3. Note the level of variability for the ten repeat tests. This suggests that even for a single lab using a single fixture, lining ratings can only be determined to within approximately ± 1. It is unclear how much of this variability is due to lining / drum friction variability and how much is due to the test setup and procedure.

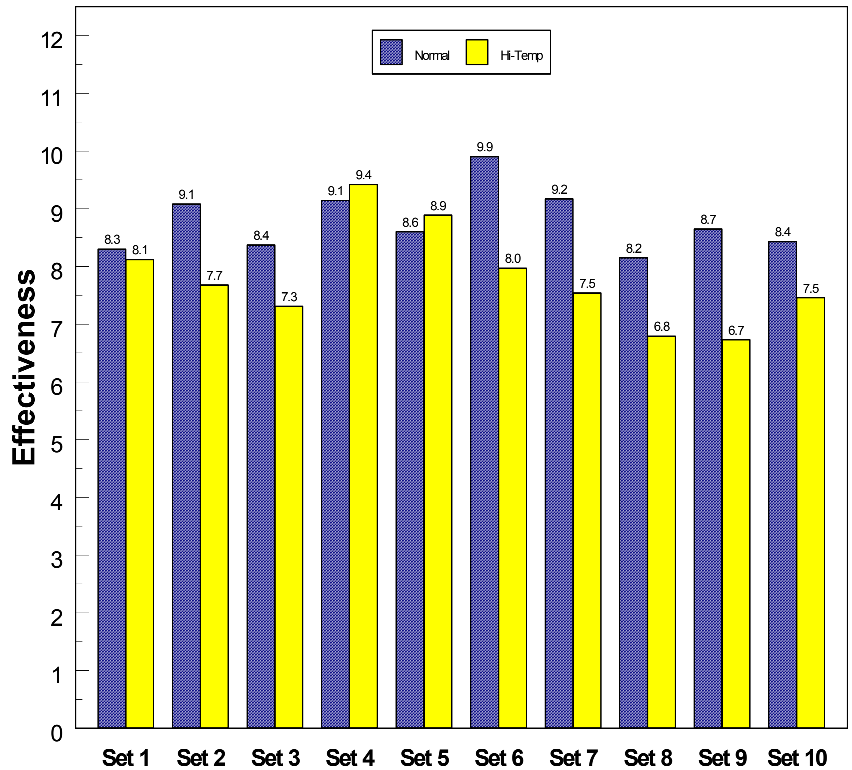


FIGURE 1.3 – Preliminary Tests of NHTSA Replacement Lining Rating Procedure

Following the preliminary testing, samples were procured both from OE and aftermarket sources for testing. To select the linings, truck sales data were reviewed to determine the most popular vehicle sold over the three previous years, which was found to be a Freightliner FLD 120. It was subsequently learned that the second most popular vehicle sold for the same time frame was the Navistar 9000 series, which uses the same brake and linings. The original equipment linings used on the drive axle of these vehicles along with two aftermarket linings, which truck equipment suppliers listed as appropriate for these vehicles, were purchased. Sufficient quantities of the linings were purchased to allow five sets of each to be tested, each set from a different production run.

The original equipment lining used on the Freightliner FLD 120 and Navistar 9000 series was the Carlisle E145A/R202. The normal and high temperature effectiveness results for this material are shown in Figure 1.4. The aftermarket linings purchased for this vehicle were Ferodo

867 and Abex 685. The results for these two materials are shown in Figure 1.5 and Figure 1.6 respectively. These results show what appears to be similar friction levels for the Carlisle and Abex materials with a higher level of test-to-test scatter in the Abex material. The Ferodo material results show somewhat lower effectiveness levels than either of the other two materials. It is unknown if this level of difference would have a significant effect on the braking performance of a vehicle.

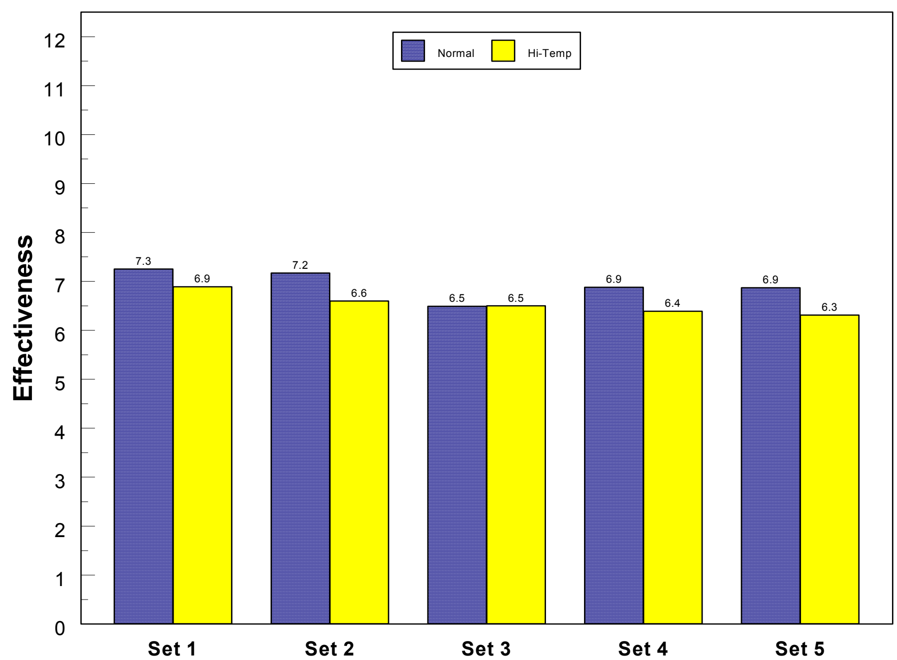


FIGURE 1.4 – NHTSA Lining Test Results for OEM Carlisle E145A/R202

A final related study by the University of Michigan Transportation Research Institute (UMTRI) was undertaken around the same time frame as this dynamometer test program. The UMTRI [8] study explored the sensitivities of the S-Cam Brake through a series of computer simulations, where this test concentrated on physical performance of the brake system under the controlled environment of the dynamometer.

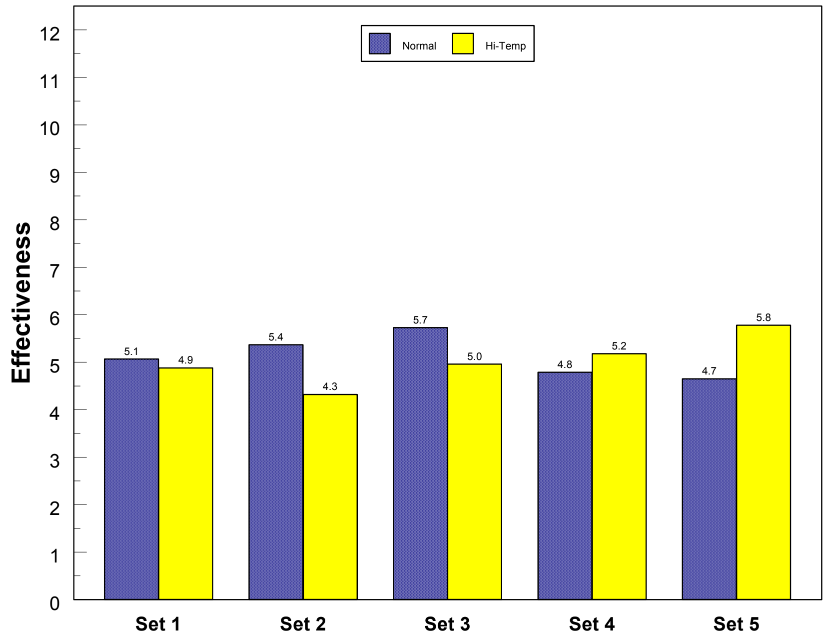


FIGURE 1.5 – NHTSA Rating Test Results for Ferodo 867 Replacement Lining

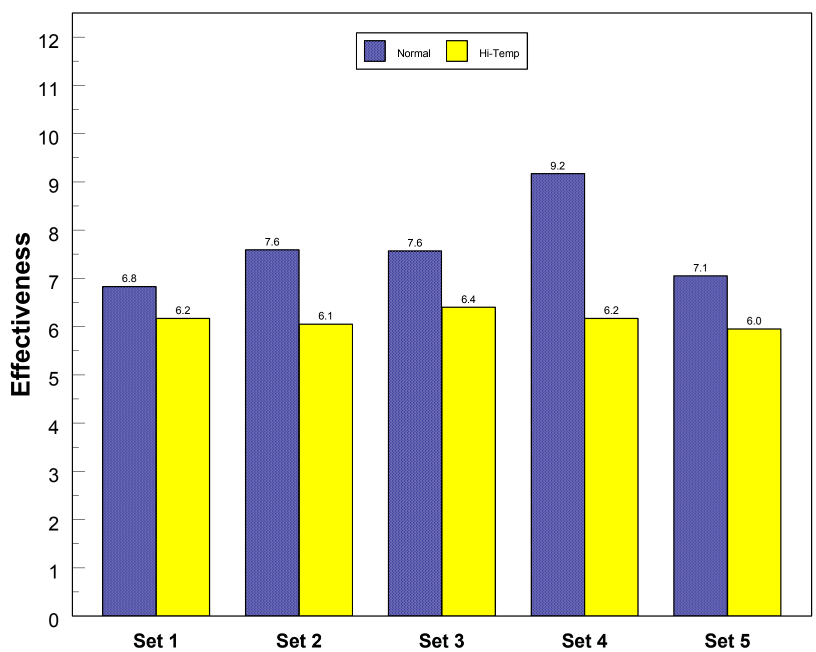


FIGURE 1.6 – NHTSA Rating Test Results for Abex 685 Replacement Lining

The UMTRI study found that 0.02 inch offsets of the drum center from the brake spider center (in either the x or y direction) could cause 3 to 4 percent changes in brake torque. This study also found that torque variation due to cam variation is directly related to its slope (inches of rise per radian of cam rotation), i.e. a 4 percent change in the slope caused a 4 percent change in the brake torque.

To summarize, an initial round-robin of brake effectiveness testing was performed with a single test fixture, drum, and lining set that was passed from one test facility to the next. Very little set-up was required by the various dynamometer operators. This initial round-robin showed good repeatability of brake effectiveness measurement for the multiple facilities using the single lining/fixture combination.

A second round-robin was performed that tested different lining materials at the various test facilities. Each test facility used its own test fixture. The variability in the results for this second round robin was very large. Other studies have followed these round-robins. These studies have shown that testing multiple samples of a lining material can produce relatively repeatable results when tested on a single test fixture at a single test site. None of the follow-up studies have been able to explain the variability seen in the second round-robin.

1.3 Rationale for the Evaluation

Characterizing heavy vehicle brake lining performance is considered to be a need by the trucking industry. While a number of efforts have been made to accomplish this, all have had some shortcomings. One of the problems with developing a scheme for rating lining performance has been developing a test fixture and procedure that, when used on brake dynamometers at different test facilities, gives similar results for a given lining. In particular, the brake effectiveness ratings found in the second round-robin testing described in the previous section had more variability than would be considered acceptable. Other follow-up studies have shown that testing multiple linings on a single test fixture at a single test site can produce results that are far less variable than those found in the second round-robin.

This study was designed to try to explain and/or eliminate some possible explanations for the variability seen in the second round-robin results. In particular, this study was aimed at determining whether or not test fixture differences are a possible explanation for the variability. Several variables and/or combination of variables could explain the variability in the second round-robin results including test fixture differences, operator differences, dynamometer differences, actual variability in lining material, variability in the drum surfaces, procedural differences, calibration errors, etc. For this study, several test fixtures were brought to VRTC for evaluation. This evaluation included a dimensional tolerance study of all the delivered test fixtures. This was followed by a series of J1802 tests using multiple linings on a sub-set of the test fixtures. It was intended that this study eliminate most of the other potential sources of variability from the evaluation by having one operator perform all the testing at one test site on a single dynamometer.

2.0 EXPERIMENTAL DESIGN

Initially, this program sought to compare four test fixtures from the original round-robin test programs. The comparison was to include a set of fixture tolerance measurements for each test fixture supplied and a series of J1802 ABrake Block Effectiveness Rating@ tests using all of the supplied fixtures and two different brake lining materials. Several samples of each lining material were to be tested. Due to budget and time constraints, the J1802 comparison test series was limited to testing two lining sets for each lining material type (two types) on two of the test fixtures. The test fixture tolerance measurements were made on each fixture.

The fixture tolerance measurements included s-cam profile, chamber force-displacement calibrations, and hole position identification of the brake spiders. The fixture measurement procedures and results are fully documented in Chapter 3.0.

The two test fixtures received from brake component manufacturers with the most complete roster of functional components were selected for the J1802 comparison test series. Two sets of linings for both lining material types evaluated, were tested using two of the test fixtures. This yielded 8 data sets from the comparison tests. The J1802 comparison test procedures and results are fully documented in Chapter 4.0.

3.0 J1802 STANDARD TEST FIXTURE COMPONENT MEASUREMENTS

3.1 J1802 Standard Test Fixtures and Components Measured

Several of the original J1802 standard test fixtures that were used for the previous two round-robin test programs, were not available for this test program. Three fixtures were received from brake component manufacturers. These were the Haldex/Midland-Grau unit from Link Engineering, the Carlisle unit from the Motion Control Industries group, and the Cooper/Abex unit from Abex Friction Products. With the VRTC unit already in house, the total number of fixtures available to measure was four. The two selected for comparison testing (Chapter 4.0), the Carlisle fixture and the Abex fixture, were the most complete sets of fixtures received from the brake component manufacturers. The VRTC fixture was used to run all of the initial conditioning procedures.

Table 3.1 lists all of the components provided with each fixture. The results of the component inspection are given in the second half of the table. VRTC provided any missing components needed to complete each fixture assembly. It should be noted that the rollers, return springs and clips, and anchor pins are standard off the shelf items that are replaced "as necessary". These items were not shared components, i.e., VRTC supplied these items, but the rollers, return springs and clips, and anchor pins were different for each fixture. The only shared component used in the comparison tests was the slack adjuster which was shared by the VRTC and Carlisle. The Haldex fixture was not evaluated in the comparison tests and therefore a service chamber did not have to be provided by VRTC to complete this fixture.

The following components are required to mount the J1802 test fixtures to the dynamometer: stub axle, hub, hub end cap, hub bearings, and hub seal. The VRTC supplied these mounting components. The mounting components were the same for each test fixture.

TABLE 3.1 – J1802 Fixture Components
(as received)

Section A	FIXTURE CONTENTS RECEIVED	VRTC		ABEX		CARLISLE		HALDEX	
		YES	NO	YES	NO	YES	NO	YES	NO
1	Spider	X		X		X		X	
2	S-Cam or Chamber Bracket	X		X		X		X	
3	S-Cam	X		X		X		X	
4	Slack Adjuster	X		X		X			X
5	Service Chamber	X		X		X			X
6	Rollers	X			X	X			X
7	Return Spring And Clips	X			X		X		X
8	Anchor Pins	X			X	X			X
Section B	**COMPONENT INSPECTION**	**OK**	**N/A**	**OK**	**N/A**	**OK**	**N/A**	**OK**	**N/A**
1	Spider	X		X		X		X	
2	S-Cam or Chamber Bracket	X		X		X		X	
3	S-Cam	X		X		X		X	
4	Slack Adjuster	X		X		C_1			X
5	Service Chamber	X		X		X			X
6	Rollers	X			X	C_2			X
8	Anchor Pins	X			X	C_2			X

C_1: Slack Adjuster - not used - wrong part - different spline pitch
C_2: Roller, Anchor Pin - not used - wrong parts/size

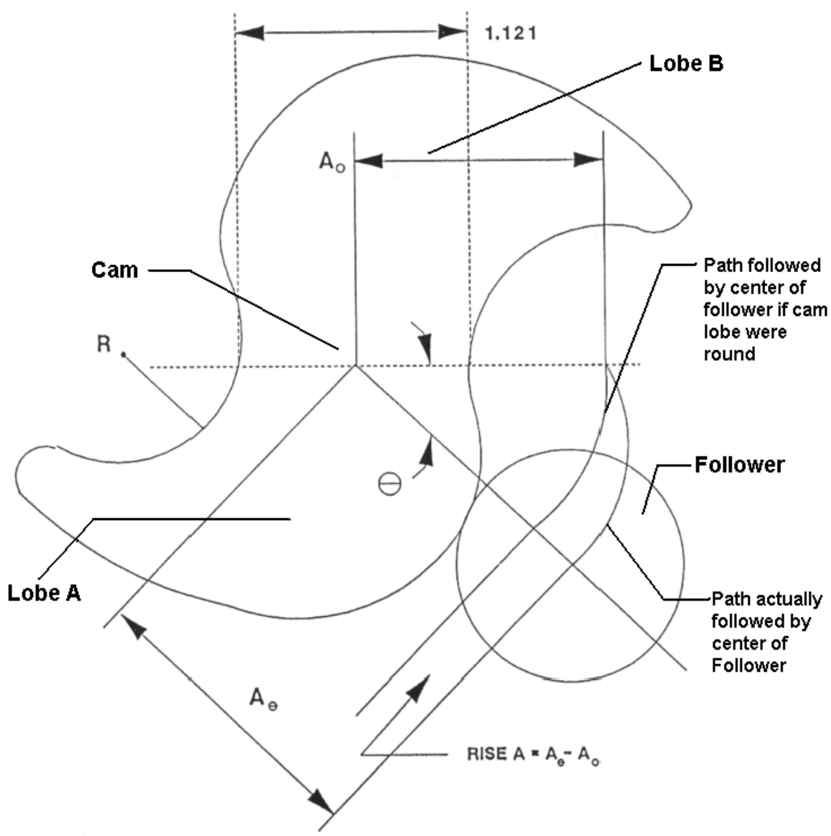
The components measured for this study were the s-cam, brake spider, and service chamber. Dimensional tolerances for the s-cam were made pre- and post-test. Dimensional tolerances were also performed on the brake spider. The service chamber measurements were really a calibration of the output force as a function of stroke and pressure. The instrumentation and procedures used to make these measurements will be discussed in Section 3.2. The results will be discussed in Section 3.3.

3.2 J1802 Test Fixture Measurement Procedures and Instrumentation

3.2.1 Cam Profile Measurements

A Cam Profiler Machine was developed at VRTC to precisely measure the rise of the s-cam lobes produced as the shaft was rotated. Figure 3.1 shows the geometry of the cam lobes. The complete Cam Profiler Machine includes the cam roller fixture, a vertical displacement transducer, a rotary potentiometer, and a data acquisition computer. The Cam Profiler is shown in Figure 3.2.

Procedurally, each s-cam is visually inspected for cracks, then mounted in the Cam Profiler Machine. The cam follower displacement and applied rotation angle are measured. The J1802 cam was designed to produce a linear relationship between the cam follower displacement and the rotation of the cam. Each s-cam has two lobes (A and B). Each lobe face is measured over a complete range of angles (0 to 150 degrees) four times: twice left of the center line and twice right of the center line. The lobes are measured before and after a test to indicate the wear encountered. A cam follower displacement versus rotation angle linear regression is calculated from the measured data.



2 = Cam Rotation Angle
A = Cam Follower Rise or Cam Follower Displacement
$A_{\cong}$= Initial Cam Follower Position at 2= 0
A_2= Follower Position

FIGURE 3.1 - Cam Dimensions

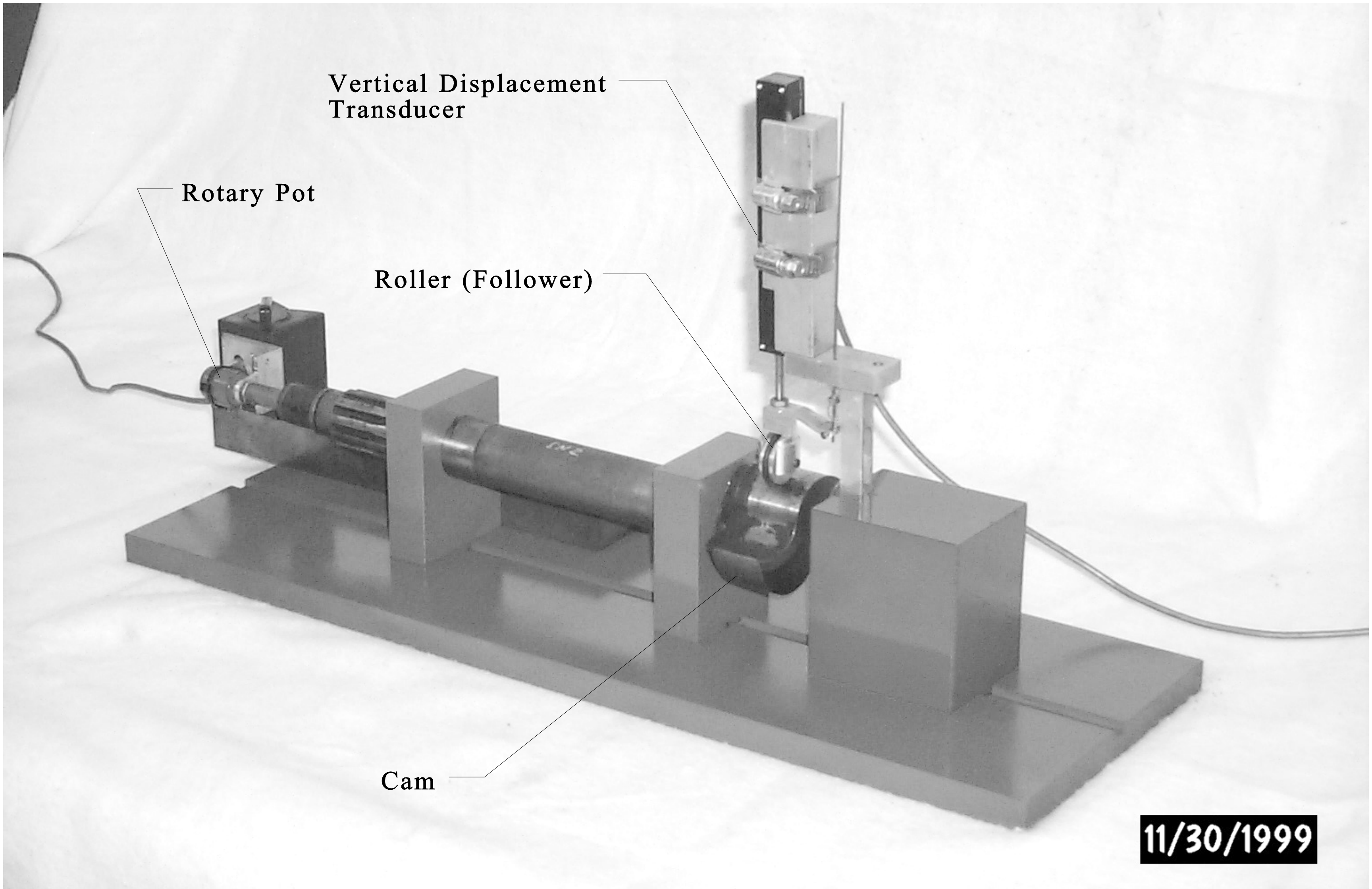


FIGURE 3.2 - VRTC Cam Profiler

3.2.2 Brake Spider Measurements

The four brake spiders (from VRTC, Abex, Carlisle, and Haldex) were sent out to a precision machine shop, Ometek, Inc., in Columbus, Ohio. Ometek installed each spider on a Kordax machine and measured the hole locations and planar run-out (warpage). Refer to the illustration in Figure 3.3 for hole locations.

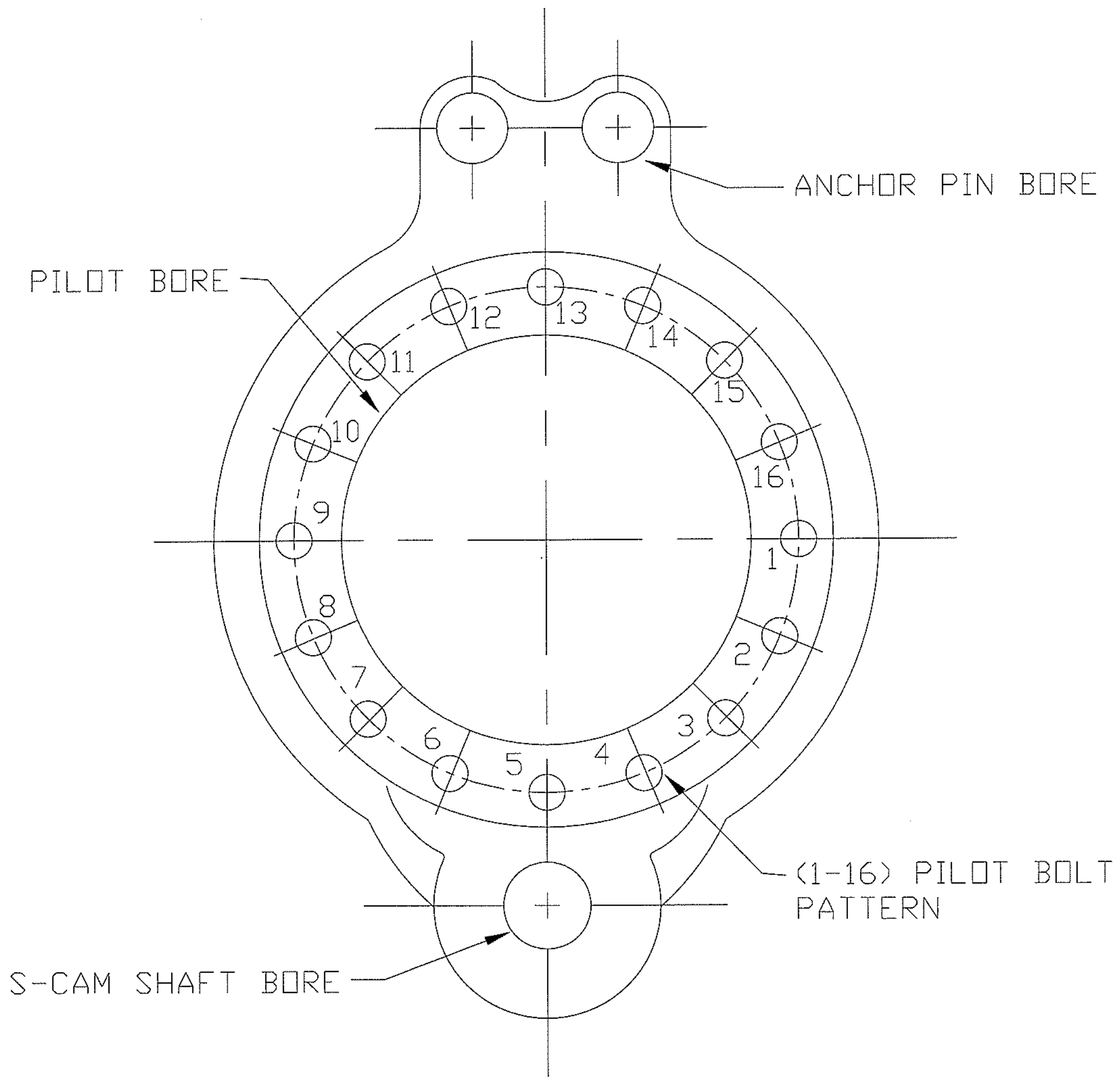


FIGURE 3.3 - Brake Spider

3.2.3 Calibrate Pushout Force on Brake Service Chambers

One of the variables employed in calculating the effectiveness of a brake lining is input torque (the other being the output torque produced by the brake assembly). While the generated braking torque is measured directly, the input torque applied to the cam shaft is not. Although this latter value could in principle be measured more directly, for example, with the use of a force pin transducer mounted in place of the pushrod clevis pin, it is instead determined indirectly in the J1802 procedure by measuring the displacement, or stroke, of the chamber pushrod as the brake is applied. The force produced for the given stroke is determined from a lookup table, and the input torque applied to the cam shaft is then calculated from that force by multiplying by the length of the slack adjuster, which in the present case is 5.5 in. This method is simple to implement, avoids the complications of cosine errors and produces accurate results.

Each of the service chambers used in the test fixtures was calibrated on a United Testing Systems, Inc. Model SFM-30 universal tensile tester to generate a lookup table file of force in pounds versus pushrod displacement in inches.

The calibration procedure is as follows: The chamber is mounted in a cage fixture, pushrod end up, on the bed of the UTS tensile tester (see Figure 3.4). The crosshead of the machine is then lowered to just contact the end of the pushrod. At that point the operator applies air pressure at a set level of 10 psi to the chamber inlet, triggers the data acquisition process and starts the crosshead retreating at a constant rate of 5.0 in/min. The pushrod extends under diaphragm pressure from the chamber a distance of 0.0 to 3.0 in (its full stroke) in a time span of approximately 36 s. At that point the pushrod and tester crosshead separate. Once the data collection process ends (a total of 45 s), the operator resets the equipment and repeats the calibration procedure at the same pressure of 10 psi, followed by two applications each at pressure levels ranging from 20 to 100 psi in 10 psi steps.

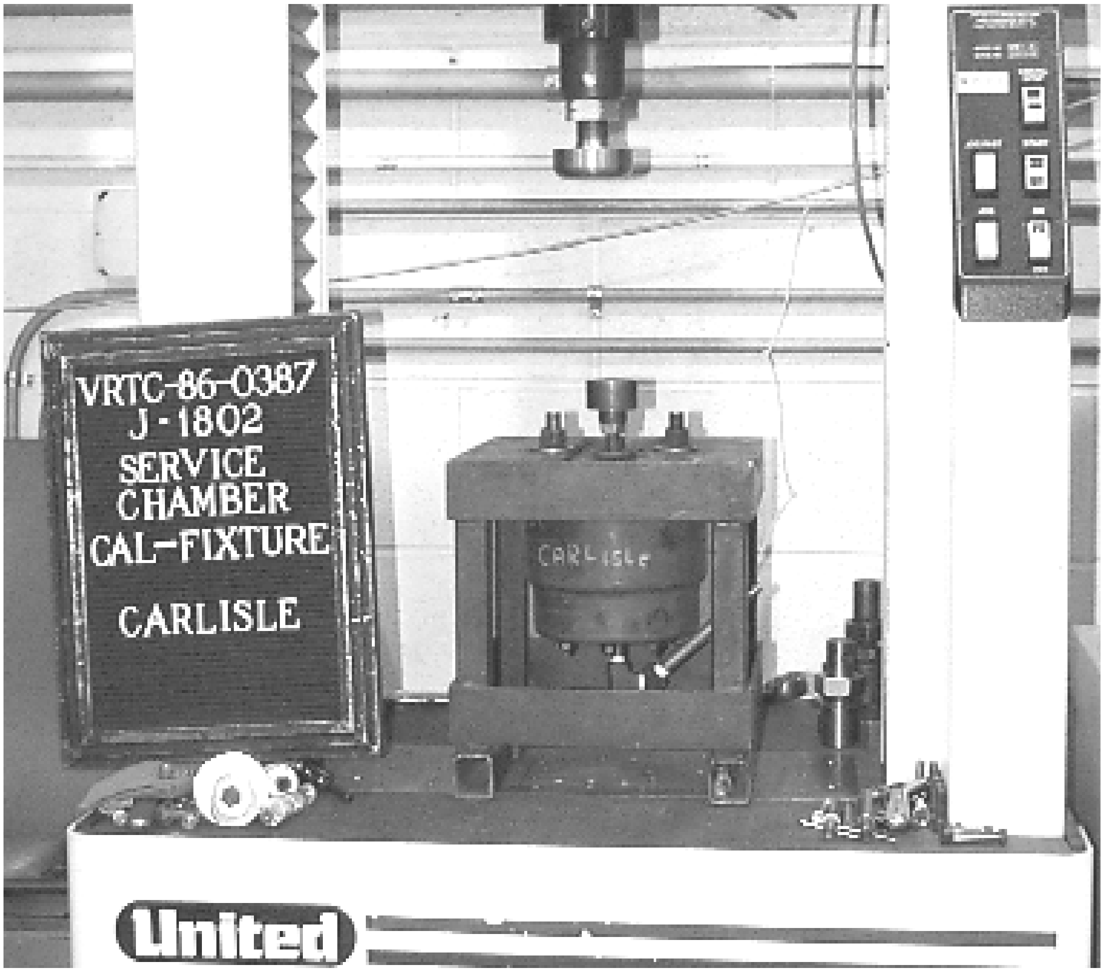


FIGURE 3.4 – United Test System for Calibrating Brake Chambers

The end result from the tensile tester is a set of 20 binary data files showing displacement, load force and chamber pressure for 10 discrete pressure levels. Figure 3.5 shows the data contained in a typical file, with the three channels plotted against time. The control pressure is initially set a small amount above the nominal value of 10, 20, etc. psi, so that once the pushrod begins to move, the line pressure rapidly drops to the nominal value and remains almost perfectly flat throughout most of the stroke, until it returns to the initial value once the limit of travel is reached. The load force similarly exhibits a long, essentially linear curve through most of the rod displacement. The control pressure is plotted versus pushrod stroke for a typical chamber in Figure 3.6. The actual stroke that occurs in the effectiveness tests is indicated with arrows. The data is very flat in the indicated region.

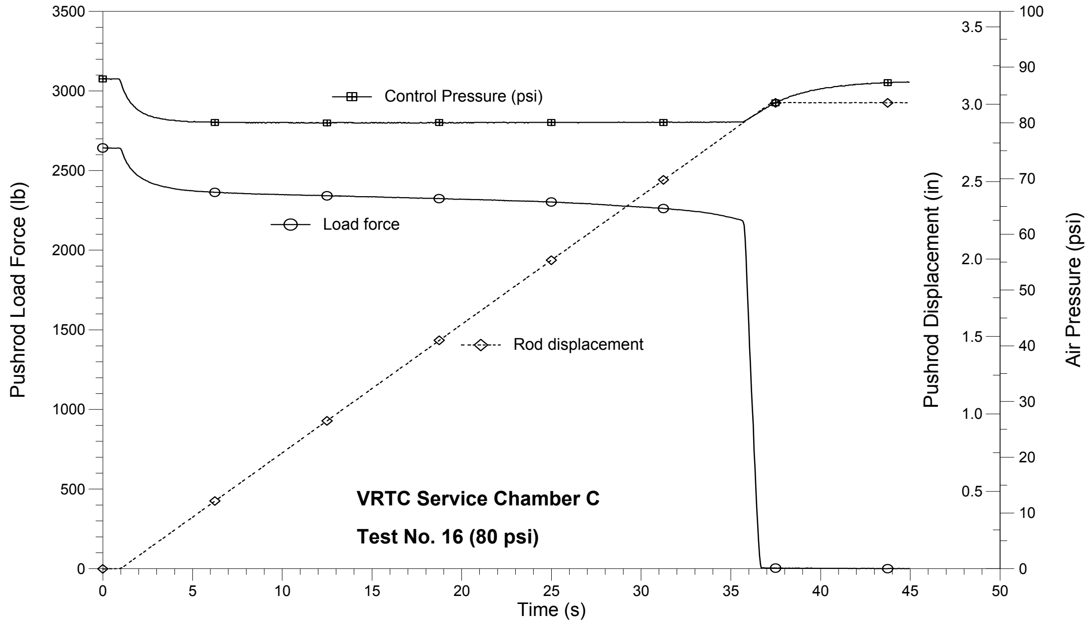


FIGURE 3.5 – Typical Measurements in a Chamber Calibration File

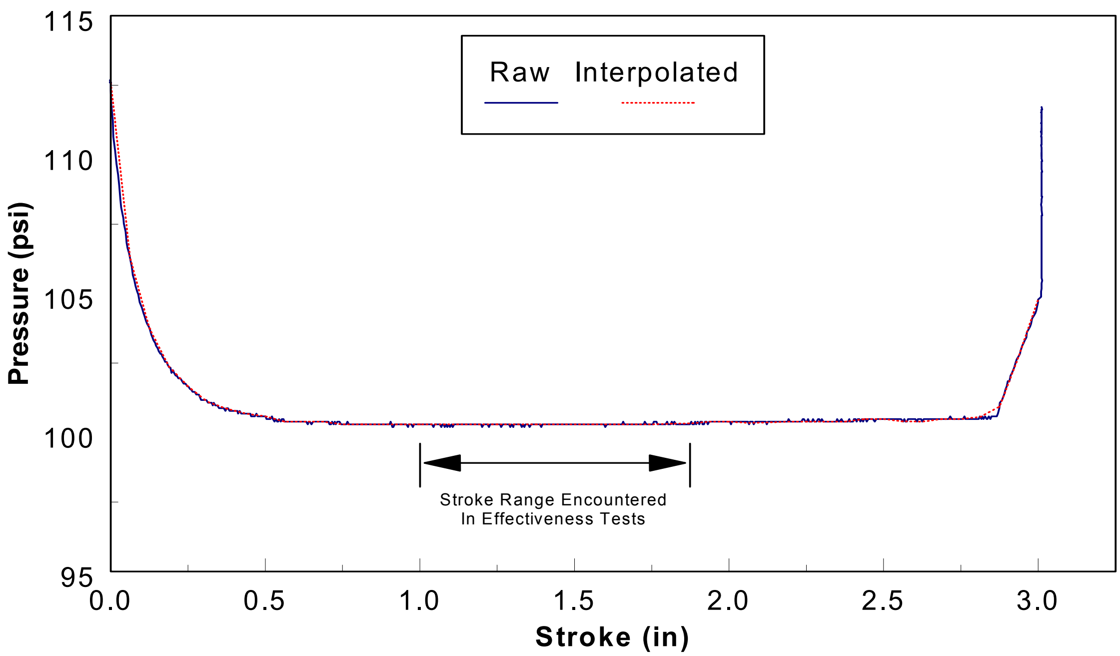


FIGURE 3.6 –Typical Curve of Chamber Pressure vs. Pushrod Stroke

Figure 3.7 shows an overlay of two tests for the same chamber at a pressure of 100 psi, with force plotted against time. The two traces are indistinguishable. Figure 3.8 shows the same tests with the pushrod force plotted against stroke instead of time. Again, the two tests display identical results. This level of repeatability was typical of all the tests conducted.

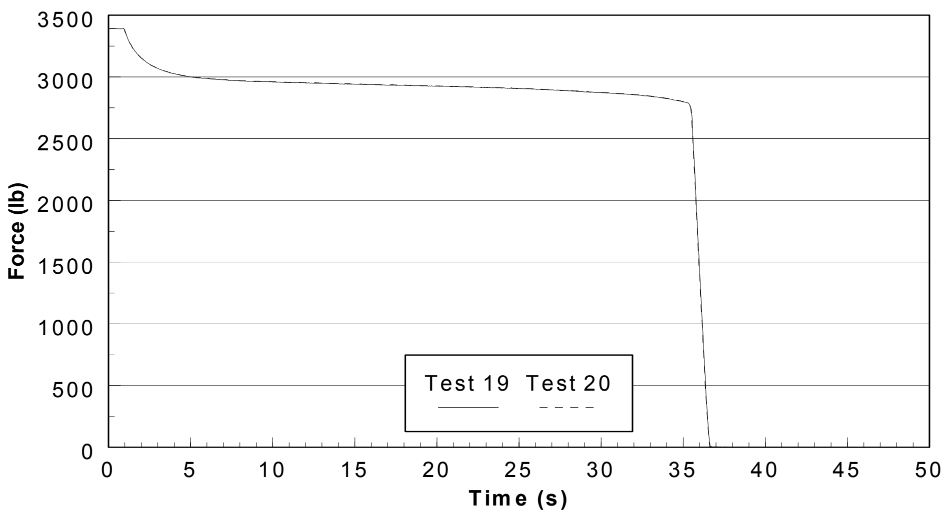


Figure 3.7 – Repeatability of Two Calibration Tests
Force as a Function of Time

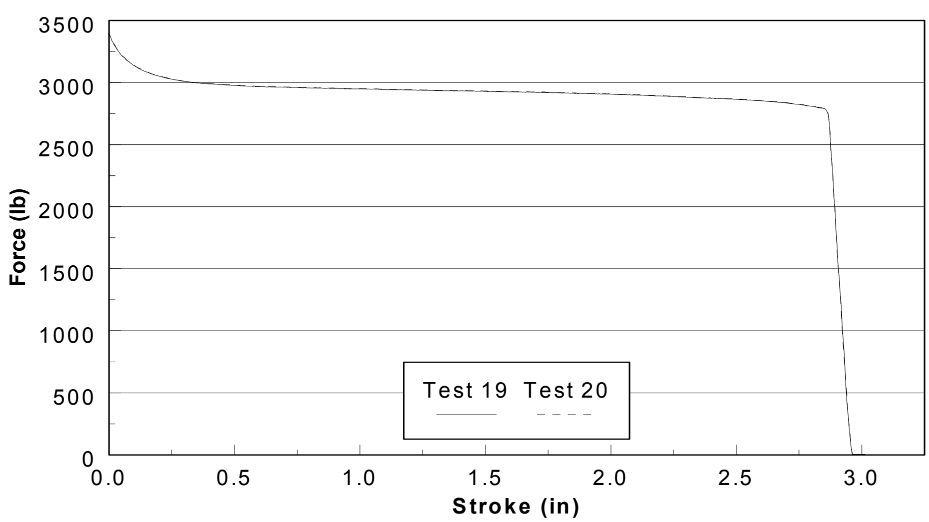


FIGURE 3.8 – Repeatability of Two Calibration Tests
Force as a Function of Stroke

The force and displacement channels for the two tests at each pressure level are averaged, thus providing a method for smoothing the curves. The data is then sub-sampled at constant displacement increments (0.0625 inches) to convert the force and displacement arrays (that are initially a function of time) into new force as a function of displacement arrays. The method of interpolation used was to select the two closest values to the desired incremental value of displacement and then perform linear interpolation between their respective force values. The raw data for Test 19, plotted force vs. stroke, is overlaid with the interpolated data from the mean of Tests 19 and 20 in Figure 3.9. The dashed line indicates the interpolation curve, and the circular symbols on the dashed line represent the discrete force values derived at each 0.0625 inches of pushrod stroke from 0.0 to 3.0 inches. The fit is very good except at the "knee" where the force drops dramatically. Although a closer fit could have been obtained by sub-sampling at a smaller stroke increment, this was deemed unnecessary, since the actual stroke values measured in the effectiveness tests are within the range of approximately 1.0 to 1.7 inches, i.e., within the highly linear zone of the calibration curve.

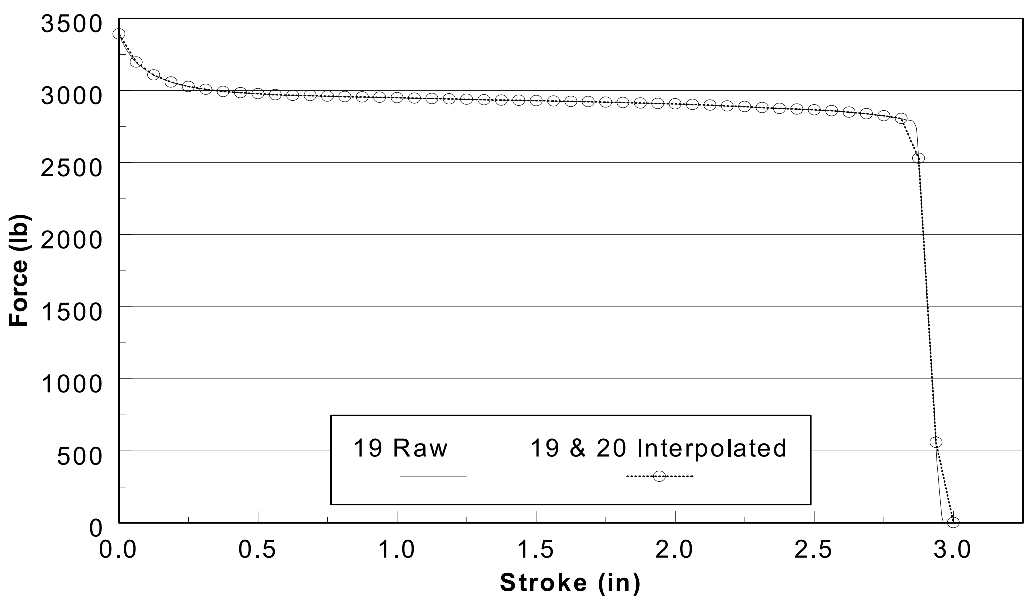


FIGURE 3.9 – Chamber Calibration Raw Data and Interpolated Values

Figure 3.10 is a plot of the final lookup table generated from all 20 calibration runs performed on one typical service chamber.

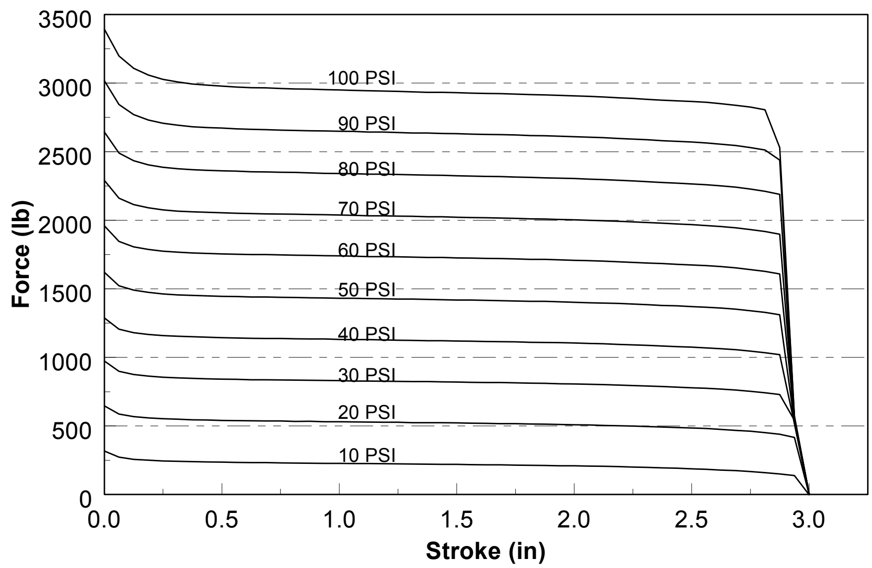


FIGURE 3.10 – Plot of Typical Service Chamber Lookup Table

For the effectiveness computation, the data reduction program takes the measured stroke value, finds the two points closest to the measured value in the lookup table and then linearly interpolates the corresponding force value.

3.3 J1802 Test Fixture Measurement Results

3.3.1 Cam Profile Measurement Results

The cam profile for each test fixture was measured using the VRTC Cam Profiler Machine. The cam follower displacement and cam rotation angle were measured. The J1802 cam is designed to produce a linear relationship between the cam follower displacement and the rotation of the cam. A linear regression of the specified J1802 Cam Profile gives a slope of 0.0089 inch/deg. The J1802 specified cam follower displacement versus rotation angle is given in Figure 3.11.

CAMSHAFT ROTATION	CAM FOLLOWER DISPLACEMENT
0	1.186
5	1.228
10	1.270
15	1.313
20	1.355
25	1.399
30	1.442
35	1.485
40	1.529
45	1.573
50	1.617
55	1.661
60	1.705
65	1.749
70	1.793
75	1.838
80	1.882
85	1.927
90	1.972
95	2.016
100	2.061
105	2.106
110	2.151
115	2.196
120	2.241
125	2.286
130	2.331
135	2.376
140	2.421
145	2.467
150	2.512

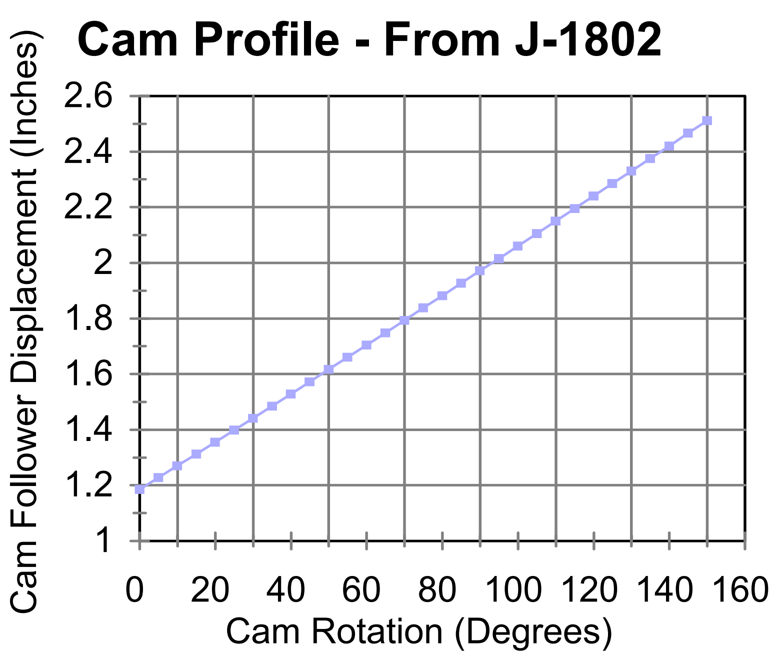


FIGURE 3.11 – Cam Profile Data From J1802

Each cam has two lobes (A and B). Each lobe was measured four times: twice left of the center line and twice right of the center line. The lobes were measured pre- and post-test. The VRTC, Abex, and Carlisle cams were the only ones tested, so the Haldex was not measured post-test. The VRTC cam was not measured pre-test. It was put into service for the lining conditioning tests prior to the Cam Profiler Machine being set up and calibrated. The collected data were first zeroed, then a linear regression was performed. The slopes for each individual measurement are given in Table 3.2.

The linear regression slope values for all of the cam profiles are very similar. The slope of the Carlisle cam did not change from pre- to post-test. The Abex cam did have a very slight slope change pre- to post-test. This may be more indicative of the measurement capabilities of the Cam Profiler Machine than it is of wear on the Abex cam. Very few tests were performed with the Abex cam and it is unlikely that any significant wear occurred. The UMTRI S-Cam simulation study [8] results would suggest that the small differences between these slopes for the different cams should only cause small differences in the brake torque developed (1 to 2 percent difference in cam profile slope should cause a 1 to 2 percent difference in brake torque).

TABLE 3.2 - Cam Profile Pre- and Post-Test Measurements

		Slope Values (in/deg)							
		Carlisle		Link/Haldex		Abex		VRTC	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Lobe	Location								
A	1	0.0091	0.0091	0.0091		0.0094	0.0090		0.0090
A	1	0.0091	0.0092	0.0091		0.0094	0.0090		0.0090
Average		0.0091	0.0091	0.0091		0.0094	0.0090		0.0090
A	2	0.0091	0.0092	0.0091		0.0094	0.0090		0.0090
A	2	0.0092	0.0092	0.0091		0.0094	0.0090		0.0090
Average		0.0091	0.0092	0.0091		0.0094	0.0090		0.0090
B	1	0.0091	0.0092	0.0090		*	0.0093		0.0091
B	1	0.0091	0.0091	0.0090		0.0095	0.0092		0.0091
Average		0.0091	0.0092	0.0090		0.0095	0.0092		0.0091
B	2	0.0092	0.0091	0.0090		0.0094	0.0092		0.0091
B	2	0.0092	0.0091	0.0090		0.0093	0.0093		0.0091
Average		0.0092	0.0091	0.0090		0.0094	0.0092		0.0091

*- This data point ignored due to a large hysteresis loop that was atypical compared to all other data

3.3.2 Brake Spider Measurement Results

A diagram of the brake spider hub is given in Figure 3.3. The diameter and center-of-hole location was measured for the pilot bore, s-cam shaft, both anchor pin bores, and 16 pilot bolt holes. The first pilot bolt hole was measured twice. The Abex test fixture measurements are given in Table 3.3. The measurements for the VRTC, Haldex, and Carlisle test fixtures are given in Appendix A.

For the Abex test fixture, the second set of measurements for the first pilot bolt hole are within 0.001 inch and 0.01 degree of the initial set of measurements. This was essentially true for the other test fixtures as well. The one exception was the angular measurement for the VRTC test fixture which was between 0.01 and 0.02 degrees different from the initial measurement.

To make comparisons the data was zeroed. The x and y center for the pilot bore were made zero and the angular position of the number 1 pilot bolt hole was made zero. The x and y positions of the center of the s-cam shaft and anchor pin bores and the angular measurement of the other 15 pilot bolt holes were adjusted accordingly. The radii of the pilot bolt holes were not adjusted. The zeroed results for the Abex test fixture are given in Table 3.4.

The minimum, maximum, and maximum-minimum values for brake spider measurements (measurements for all four brake spiders) are given in Table 3.5. All of the diameter measurements show that the fixtures have less than 0.004 inch difference in size. The x and y locations of the s-cam shaft and anchor pin bore centers are less than 0.01 inch different in location. The radial locations of the pilot bolt holes vary less than 0.007 inch and the angular locations change less than 0.15 degrees for all four measured fixtures. The UMTRI S-Cam simulation study found that 0.02 inch offsets of the drum center from the brake spider center (in either the x or y direction) could cause 3 to 4 percent changes in brake torque. The drum center offset from the brake spider center was not measured in this study, but brake spider dimensional tolerances for the four fixtures measured are less than half the 0.02 inch offset and therefore should contribute less than 1 to 2 percent to differences in measured brake lining effectiveness.

TABLE 3.3 - Abex Brake Spider Measurement Values

		Location:	
	Dia. (inch)	**X (inch)**	**Y (inch)**
Pilot Bore	6.7532	0.0000	-0.0005
S-Cam Shaft - F	1.5001	5.9969	0.0001
S-Cam Shaft - R	1.5003	5.9972	0.0000
Anchor Pin Bore - A - F	1.2501	-6.7523	1.2502
Anchor Pin Bore - A - R	1.2502	-6.7530	1.2509
Anchor Pin Bore - B - F	1.2503	-6.7520	-1.2490
Anchor Pin Bore - B - R	1.2499	-6.7530	-1.2490
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6551	4.1215	-0.1880
2	0.6588	4.1171	22.3540
3	0.6594	4.1180	44.9140
4	0.6601	4.1186	67.4670
5	0.6595	4.1215	89.9640
6	0.6582	4.1236	112.4530
7	0.6544	4.1260	135.0080
8	0.6559	4.1278	157.4030
9	0.6561	4.1314	179.8660
10	0.6560	4.1264	-157.6650
11	0.6578	4.1298	-135.2170
12	0.6592	4.1259	-112.6890
13	0.6565	4.1243	-90.2170
14	0.6608	4.1184	-67.7340
15	0.6582	4.1227	-45.2180
16	0.6576	4.1194	-22.7230
1 - Repeat	0.6558	4.1209	-0.1920

TABLE 3.4 - Abex Brake Spider Zeroed Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7532	0.0000	0.0000
S-Cam Shaft - F	1.5001	5.9969	0.0006
S-Cam Shaft - R	1.5003	5.9972	0.0005
Anchor Pin Bore - A - F	1.2501	-6.7523	1.2507
Anchor Pin Bore - A - R	1.2502	-6.753	1.2514
Anchor Pin Bore - B - F	1.2503	-6.752	-1.2485
Anchor Pin Bore - B - R	1.2499	-6.753	-1.2485
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6551	4.1215	0.0000
2	0.6588	4.1171	22.5420
3	0.6594	4.118	45.1020
4	0.6601	4.1186	67.6550
5	0.6595	4.1215	90.1520
6	0.6582	4.1236	112.6410
7	0.6544	4.1260	135.1960
8	0.6559	4.1278	157.5910
9	0.6561	4.1314	-179.9460
10	0.6560	4.1264	-157.4770
11	0.6578	4.1298	-135.0290
12	0.6592	4.1259	-112.5010
13	0.6565	4.1243	-90.0290
14	0.6608	4.1184	-67.5460
15	0.6582	4.1227	-45.0300
16	0.6576	4.1194	-22.5350
1 - Repeat	0.6558	4.1209	-0.0040

TABLE 3.5 - Minimum, Maximum, and Maximum-Minimum Brake Spider Zeroed Measured Values for all Four Measured Fixtures

	MIN			MAX			MAX-MIN		
	Diameter (inch)	X (inch)	Y (inch)	Diameter (inch)	X (inch)	Y (inch)	Diameter (inch)	X (inch)	Y (inch)
Pilot Bore	6.7530	0.0000	0.0000	6.7540	0.0000	0.0000	0.0010	0.0000	0.0000
S-Cam Shaft - F	1.5001	5.9927	-0.0004	1.5033	5.9971	0.0012	0.0032	0.0044	0.0016
S-Cam Shaft - R	1.5003	5.9940	-0.0018	1.5036	5.9975	0.0005	0.0033	0.0035	0.0023
Anchor Pin Bore - A - F	1.2497	-6.7618	1.2491	1.2528	-6.7523	1.2540	0.0031	0.0095	0.0049
Anchor Pin Bore - A - R	1.2496	-6.7610	1.2487	1.2510	-6.7530	1.2544	0.0014	0.0080	0.0057
Anchor Pin Bore - B - F	1.2496	-6.7574	-1.2485	1.2523	-6.7520	-1.2442	0.0027	0.0054	0.0043
Anchor Pin Bore - B - R	1.2495	-6.7562	-1.2499	1.2515	-6.7530	-1.2456	0.0020	0.0032	0.0043
Pilot Bolt No.	**Diameter (inch)**	**Radius (inch)**	**Angle (deg)**	**Diameter (inch)**	**Radius (inch)**	**Angle (deg)**	**Diameter (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6551	4.1206	0.00	0.6563	4.1269	0.00	0.0012	0.0063	0.00
2	0.6576	4.1171	22.50	0.6588	4.1238	22.56	0.0012	0.0067	0.06
3	0.6583	4.1180	45.00	0.6600	4.1248	45.10	0.0017	0.0068	0.10
4	0.6594	4.1186	67.57	0.6602	4.1251	67.68	0.0008	0.0065	0.11
5	0.6588	4.1213	90.00	0.6595	4.1222	90.15	0.0007	0.0009	0.15
6	0.6578	4.1236	112.53	0.6583	4.1271	112.64	0.0005	0.0035	0.11
7	0.6544	4.1235	135.06	0.6572	4.1274	135.20	0.0028	0.0039	0.14
8	0.6559	4.1252	157.48	0.6593	4.1308	157.59	0.0034	0.0056	0.12
9	0.6559	4.1276	-180.00	0.6561	4.1331	-179.95	0.0002	0.0055	0.05
10	0.6558	4.1218	-157.53	0.6565	4.1264	-157.48	0.0007	0.0046	0.05
11	0.6575	4.1251	-135.08	0.6596	4.1298	-135.03	0.0021	0.0047	0.05
12	0.6557	4.1237	-112.59	0.6592	4.1263	-112.50	0.0035	0.0026	0.08
13	0.6565	4.1207	-90.07	0.6575	4.1243	-90.01	0.0010	0.0036	0.06
14	0.6607	4.1164	-67.59	0.6618	4.1192	-67.52	0.0011	0.0028	0.07
15	0.6578	4.1208	-45.05	0.6585	4.1235	-45.01	0.0007	0.0027	0.04
16	0.6573	4.1177	-22.54	0.6580	4.1227	-22.50	0.0007	0.0050	0.03
1 – Repeat	0.6558	4.1209	-0.02	0.6568	4.1272	0.00	0.0010	0.0063	0.03

3.3.3 Brake Service Chamber Calibration Results

The chamber lookup tables are plotted in Figures 3.12 through 3.14 for the Abex, Carlisle, and VRTC chambers respectively. The effectiveness tests are performed with stroke values in the approximate range of 1.0 to 1.7 inches. All of the lookup tables are highly linear over this range. Figure 3.15 is an overlay for all three chamber lookup tables. Over the range of strokes used for effectiveness measurements, all three service chambers produced similar amounts of force for a given air pressure. This is especially true at lower pressures. The VRTC values separate from the other two at higher pressures. It should be noted that the similarity between the service chambers is not a necessity to produce similar effectiveness values. The effectiveness is determined by the slope of the output force (torque) versus input force (torque). Therefore, the slight differences in the service chamber calibration curves should not affect measured effectiveness values.

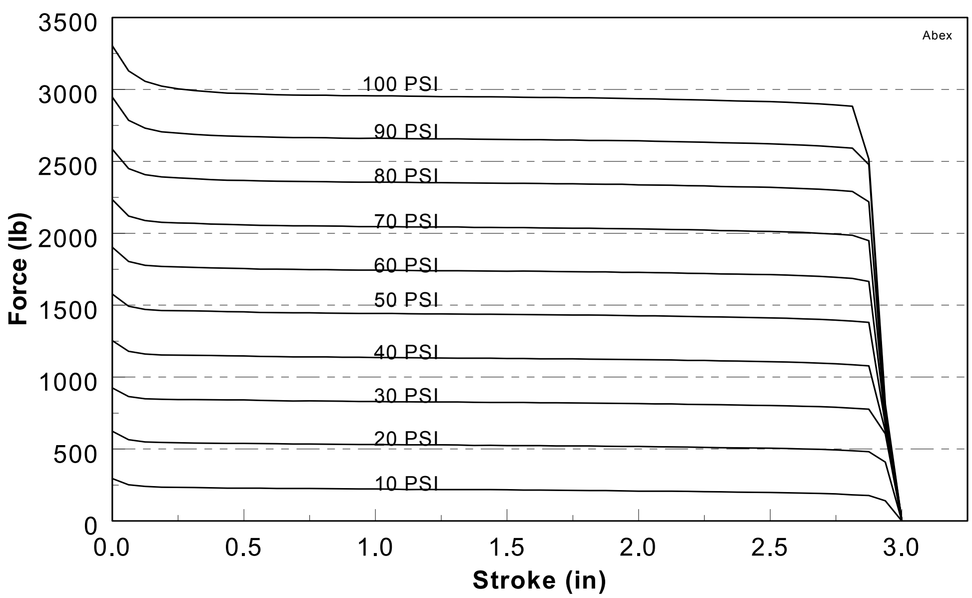


FIGURE 3.12 – Lookup Table Values for Abex Service Chamber

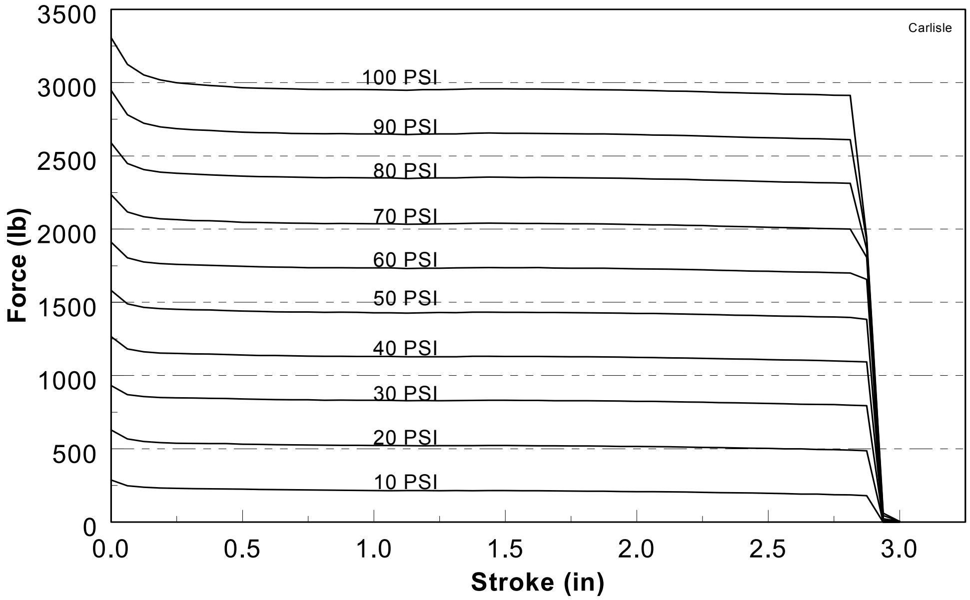


FIGURE 3.13 – Lookup Table Values for Carlisle Service Chamber

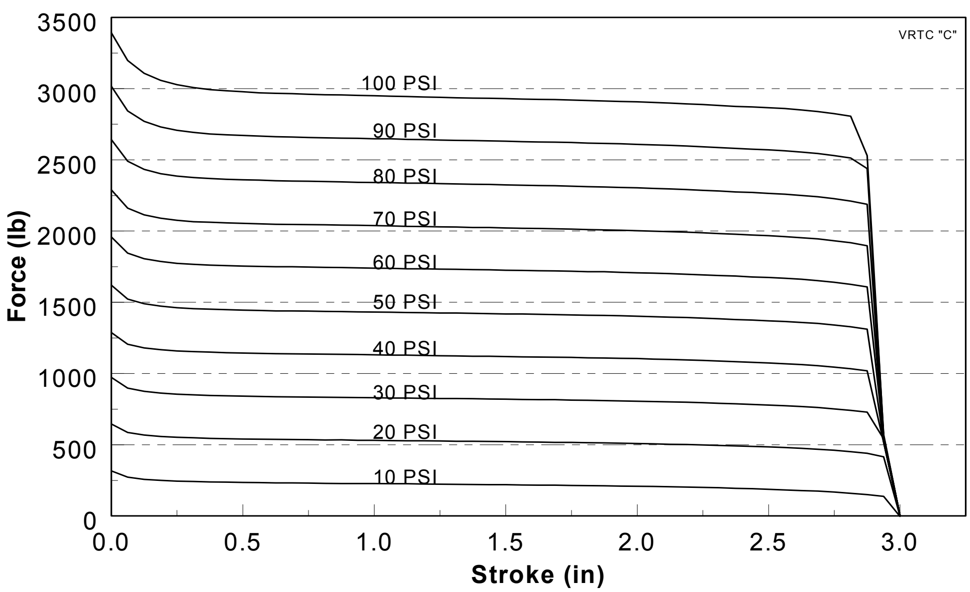


FIGURE 3.14 – Lookup Table Values for VRTC Service Chamber

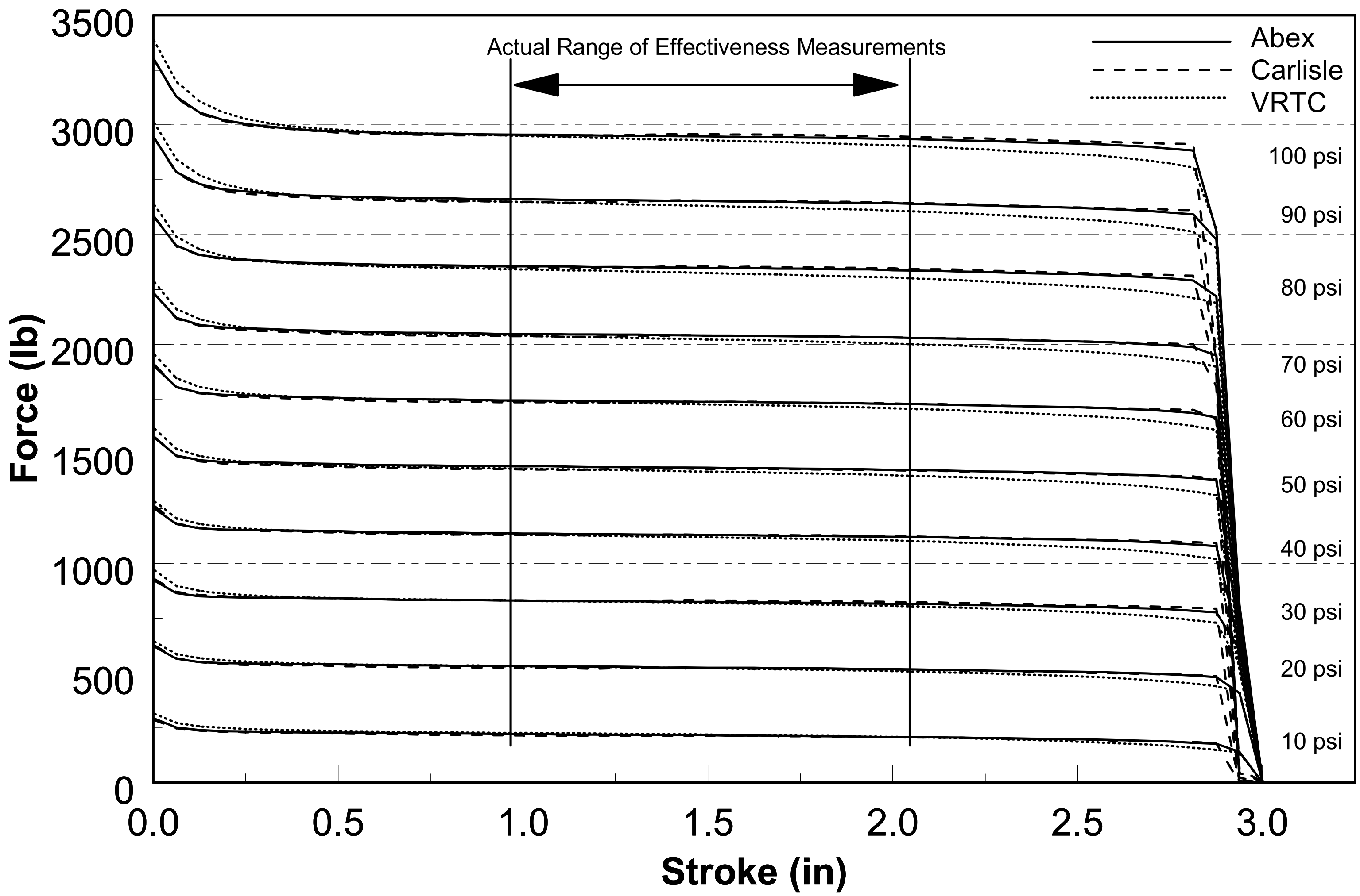


Figure 3.15 – Overlay of Lookup Table Values for all Service Chambers used in this study

4.0 J1802 TEST FIXTURE EVALUATION - COMPARISON TESTING

4.1 J1802 Comparison Testing Objectives and Testing Overview

The Carlisle and Abex test fixtures were selected for the J1802 comparison test series. Two sets of linings for both BrakePro and Haldex brand lining materials were tested using these test fixtures. This yielded 8 data sets from the comparison tests. The objective of this test sequence was to determine if there were differences in lining effectiveness ratings measured using these two fixtures.

In preparation for these comparison tests, the brake linings were conditioned using the J1802 test procedure and the VRTC test fixture. Previous research has shown that the brake effectiveness values will change with conditioning. It was thought by the authors that running a complete J1802 test sequence on the brake linings would produce a more stable lining material. The more stable lining material was necessary to allow a better comparison of J1802 effectiveness values found using the Carlisle and Abex fixtures. A total of four linings for each brand evaluated were conditioned and then two of the four for each brand were randomly selected for the comparison tests.

The instrumentation, procedures, and results for the comparison tests will be fully discussed below.

4.2 J1802 Comparison Testing Components

The following list of testing components will be discussed in Sections 4.2.1 - 4.2.5: dynamometer operator experience, brake block specimens, Greening Inertia Dynamometer, sensor and data channels, and the data acquisition and reduction system.

4.2.1 Dynamometer Operator Experience

The dynamometer operator is responsible for conducting the test sequences performed to determine the brake effectiveness values. Since the operator is far from just being a component of the testing, it is important to mention operator experience. The dynamometer operator that performed the tests for this study has 18 years of dynamometer experience. His background includes nearly thirty years as a Master Machinist and eighteen years as the lead operator of the Greening Inertia Brake Dynamometer at VRTC. He is highly proficient in all phases of brake dynamometer testing, including setup configuration, system calibration, routine and special test procedures, component measurement, and in-depth diagnostics and maintenance.

4.2.2 Brake Block Specimens

Two types of brake blocks were used for the tests. The J1802 type blocks were provided by BrakePro, Ltd. and Haldex/Midland/Friction Materials Research and Development Center. BrakePro supplied blocks with an edge code of “CM22 A1FF 4515 CD”. Haldex supplied blocks with an edge code of “2015-1802". Each supplier provided enough blocks for 3 axle sets, or 6 wheels. Each pair of blocks were randomly removed from the shipping boxes, visually inspected for cracks and chips, and assigned a sequential identification number. See Section 4.3.1 for the detailed procedures pertaining to the brake blocks.

4.2.3 Greening Inertia Brake Dynamometer

The VRTC Greening Inertia Dynamometer is one of two units originally built for the National Bureau of Standards (now NIST) in Washington, D.C. The VRTC unit is an inertia type, double-ended brake dynamometer (see photograph in Figure 4.1). It was configured for this test series with 845 slug-feet squared of inertia in the discs, shafts, and a single brake drum assembly. The system was powered from a 145 kVA isolation transformer that prevents electrical interaction with other equipment in the building. A recently installed Allen Bradley 1395 DC Motor Controller regulated the speed of the 125 horsepower dynamometer drive motor. A 64-bit drum programmer sequenced the steps of the burnish and effectiveness procedures, as was done in the previous two round-robin test sequences. The system was equipped with several tools to perform daily calibrations on currently used channels. The entire brake dynamometer is fully calibrated on an annual basis to ensure system integrity.

FIGURE 4.1 – Greening Inertia Brake Dynamometer

4.2.4 Sensors and Data Channels

Several physical parameters were measured during the dynamometer tests including rotational velocity (rpm), applied air pressure, pushrod displacement (stroke), generated braking torque, lining temperature, drum temperature, and both cooling air temperature and velocity.

The rotational velocity (rpm) of the combined inertial mass was measured in two ways. An Allen Bradley incremental optical encoder measured the rpm and directly controlled the drive motor operation through comparison to the programmed setpoints. The output from a Labeco optical encoder (also measuring the rpm) was directed to both an operator panel display and the data acquisition channel, where the data channel was first converted from a pulse frequency to an analog voltage level before recording. A rolling radius of 19.7 inches is factored into the rpm conversion so 1 mile per hour (mph) equals 8.53 revolutions per minute (rpm). With this tire equivalent of 511.9 revolutions per mile, a rotational velocity of 511.9 rpm equals a ground speed of 60 mph.

The applied air pressure was measured at the inlet to the rotochamber being tested. A close-coupled pneumatic tee was installed between the air supply line and the inlet port to the chamber. A Sensotec 200 psig rated pressure transducer was connected to the tee to provide feedback for constant pressure control during the effectiveness tests. A dedicated air compressor supplied a constant pressure of 185 psi to a 5,000 cubic inch reservoir that was mounted near the service chamber and adjacent to the dynamometer. This pressurized storage tank provided a chamber air pressure rise rate of 60 psi per quarter second (240 psi/sec), when controlled through a pneumatic servo valve, which was within the J1802 range of 175-265 psi/sec.

The rotochamber pushrod displacement (stroke) was measured during the tests with a 4 inch linear Penny-Giles potentiometer. The potentiometer was mounted parallel to the stroke of the rotochamber pushrod on the chamber mounting bracket. It was attached at a right angle to the manual slack adjuster at the clevis pin.

The stub axle was rigidly mounted to a 12.0 inch moment arm that pushed tangentially against a 10,000 pound, horizontally mounted, load cell. The brake torque generated during each stop was measured in pound-feet, to a maximum capacity of 10,000 pound-feet. These torque values were recorded by the data system, and compared to the programmed torque requirement during constant deceleration “burnish” stops as a controlling function.

The uniform measurement of the drum temperature was discussed with the Heavy Duty Brake Manufacturers’ Council (HDBMC) at the onset of this project. It was determined that the new thermocouple array, developed at VRTC in the mid-1990's, would be applied for this test series.

The “array” was configured by welding groups of three “J-type” thermocouples across the face of the drum, at 120 degree increments around the outer circumference, (see photographs in Figures 4.2 and 4.7).

The three thermocouples mounted across the face were spaced 1-1/4 inches apart, with 7/8 inch spacing between the nearest weldments of adjacent thermocouples. The inboard thermocouples were centered 4.00 inches from the inside edge of the drum. A metal positioning guide was used to lay out the three thermocouple positions for each drum configured.

Each of the three thermocouples around one circumferential ring were paralleled as a single data channel and recorded. Each ring temperature indicated the average temperature at a uniform distance from the inside edge of the drum. Since there was some variation in the three ring temperatures, each of the three ring channels were averaged into an “average” control channel to indicate an overall average drum temperature. This “average” control channel was the master reference channel for data collection and for initial brake temperature control of the brake application.

Lining temperatures were measured by placing a ”J-type” QuikTip thermocouple in each lining, using the old drum plug thermocouple mounting procedure, to a depth of 0.060 inch. The thermocouples were placed near the center of the brake block area with the leads protruding away from the drum.

Two additional parameters were measured pertaining to the ambient conditions occurring near the brake under test. A venturi tube inside the air circulation duct indicated the speed of the air flowing a few inches ahead of the brake drum. The airspeed was maintained at 22.5 mph. A “J-type” thermocouple, also mounted in the air duct, indicated the temperature of the air used to cool the brake. An air damper system regulated the air temperature to between 90-95 degrees Fahrenheit, which was within the J1802 specified range of 77-104 degrees F.

The S-cam supplied by Abex was strain gaged for making direct input torque measurements. The unit was used for testing in the “as received” condition, as no calibration fixture was available to measure the sensitivity. A resistor close to the value specified for shunt calibration by Abex was applied to set the amplifier gain. Due to the limited gain accuracy of the calibration procedure, the data collected from this Abex torque channel was collected only as a reference.

4.2.5 Data Acquisition and Reduction System

A MicroVAX 3600 Computer Data Acquisition System logged the data. The raw signals from the sensors were conditioned with Analog Devices 3B18 Strain Gage amplifiers and 3B47 Thermocouple amplifiers. The conditioned signals were digitized at a rate of 25 samples per second per channel, with an ADAC-1023 Q-bus type 12-bit digitizer card. The data were converted to engineering units and a brief summary of results displayed on the CRT after each constant pressure brake application during the effectiveness test series. Input torque was calculated using chamber stroke data, input pressure data, and calibration data from the tables generated during the pretest chamber calibrations.

4.3 J1802 Comparison Testing Procedures

The following procedures will be discussed in Sections 4.3.1 - 4.3.5: receiving and preparing blocks, machining brake arch before burnish, measuring brake arch on assembled shoes, installation and conditioning on dynamometer, and fixture comparison test.

4.3.1 Receiving and Preparing Blocks for Test

Two brands of J1802 type brake blocks were received, BrakePro and Haldex/Midland. The red edge colored blocks supplied by BrakePro listed an edge code of “CM22 A1FF 4515 CD”. They were formulated as quiet bus linings for J1802 applications. The codes on the back of the blocks were ANC-491A and CAM-81623A. The black edge colored blocks were supplied by Haldex with an edge code of “2015-1802". There were no codes on the back of the Haldex blocks. Both suppliers provided six wheel sets of blocks.

Each group of blocks were randomly removed (in anchor block and cam block designated pairs) from the shipping containers, visually inspected for uniformity in manufacturing and for both cracks and chips from handling. They were then assigned sequential identification numbers. The cam blocks were assigned odd numbers and the anchor blocks, even numbers. The numeric assignments are listed in Table 4.1.

TABLE 4.1 – Assigned Block Numbers
Shoe Set Description - Before Grinding

Brand	Shoe	Lead Shoe		Trail Shoe		Block
Name	**Set**	**Cam**	**Anchor**	**Cam**	**Anchor**	**Condition**
BrakePro	1	1	2	3	4	ok
BrakePro	2	5	6	7	8	ok
BrakePro	3	9	10	11	12	ok
BrakePro	4	13	14	15	16	ok
BrakePro	5	17	18	19	20	ok
BrakePro	6	21	22	23	24	ok
Haldex	7	25	26	27	28	ok
Haldex	8	29	30	31	32	ok
Haldex	9	33	34	35	36	ok
Haldex	10	37	38	39	40	ok
Haldex	11	41	42	43	44	ok
Haldex	12	45	46	47	48	ok

In preparation for cutting to SAE radius, all twelve wheel sets of blocks were bolted with a torque of 90-95 inch-pounds (a nominal 80 to 100 inch-pound range is specified in Appendix B of the “SAE J1802 “ standard) onto standard cast Rockwell Reference Shoes as described in SAE J1802-1 “Test Component Specifications,” [9]. A photograph of a typical shoe assembly is shown in Figure 4.2. Each assembly was visually inspected before banding on a pallet for shipment to be cut to radius.

FIGURE 4.2 – Drum and Shoe Assemblies

4.3.2 Machining Brake Arch Before Conditioning

After being mounted on the shoes, the lining blocks (shoe assemblies) were transported to Greening Testing Laboratories, Inc. to be machined to the specific profile that was used in the earlier phases of the J1802 study. They were turned on an engine lathe to achieve nearly 100% contact between the brake linings and the drum around the entire circumference of the brake. The lathe cut has been found to provide a more uniform finish than the "grind" finish obtained when using a spindle mount on a Sheppard Thompson grinder.

The lathe was configured to cut the J1802 specified 8.228 to 8.232 inch radius (see Figure 4.3), while maintaining the shoe assembly in a "brake applied" position. This "fit" of brake lining to drum is considered by industry to be of critical importance for repeatability of results in dynamometer tests. Typically, such close contact is achieved by extensively repeating burnish stops. The turning of brake linings is not the industry norm, but Greening maintains the mounting fixtures and skills necessary to perform the operation and achieve the appropriate results.

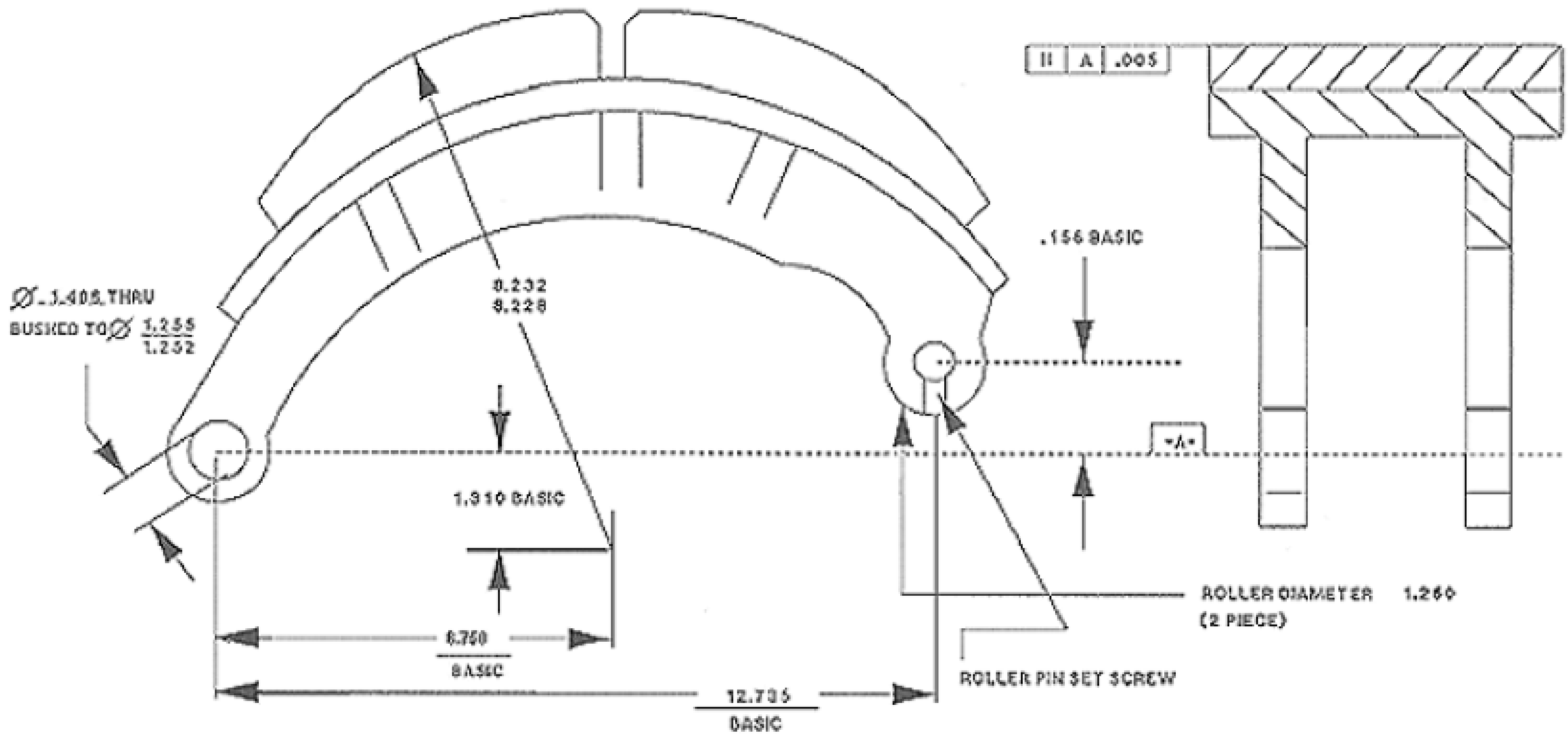


FIGURE 4.3 - Required SAE J1802 Radius of Curvature

In an effort to obtain maximum dimensional similarity, VRTC requested that the cutting procedure be performed all at one setting, with the same machine, and the cutting be performed by the same machinist.

4.3.3 Measuring Brake Arch on Assembled Shoes

A brake lining radius fixture was developed and fabricated at VRTC (see photograph in Figure 4.4). Each shoe assembly is measured with this fixture after the lining has been machined to the prescribed arch, but before a conditioning burnish is run. The measurement is performed by mounting the machined shoe assembly onto the radius fixture at the cam and anchor pin locations. An overhead radial arm indicator is moved to the calibration rest and the indicator dial set to 8.227 inches (the calibration point of this fixture).

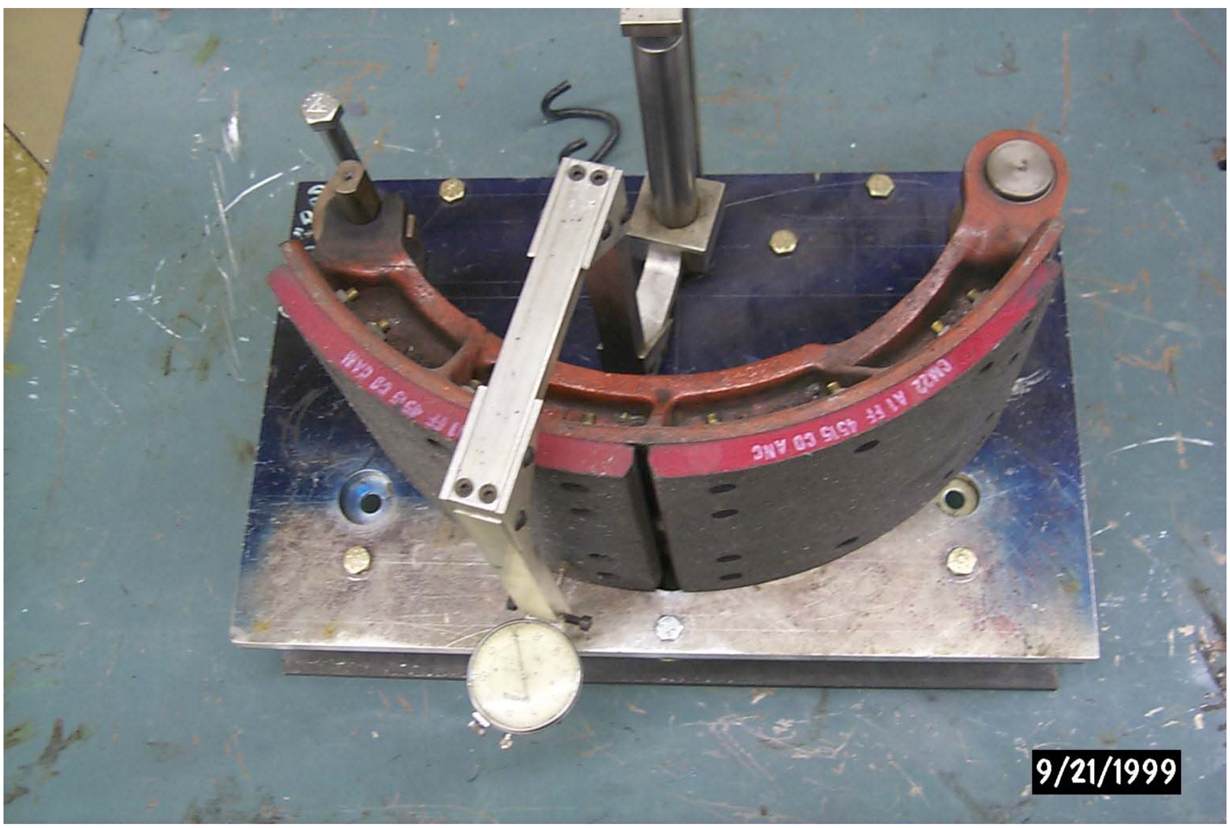


FIGURE 4.4 – VRTC Lining Radius Fixture

The arm is then hand indexed to sweep the locations shown in Figure 4.5. Measurements are made at six locations around the perimeter of the arch, each at three different levels above the fixture baseplate, which correspond to lateral midway points between the mounting holes of the blocks. The parameters are tabulated and a standard deviation is calculated to identify the surface uniformity of the cut blocks. The worst case tolerance of the radius fixture is believed to be ±0.002 inches radially, which occurs between the lower position measurements and the high position measurements.

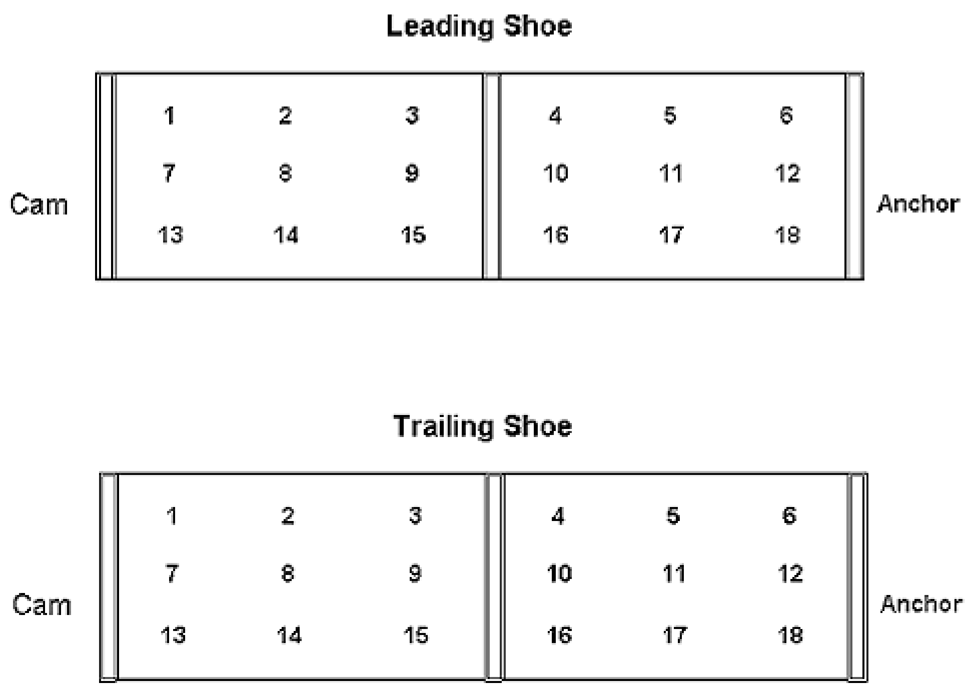


FIGURE 4.5 - Radius Locations on Each Shoe

The initial lining radius measurements are compared to the J1802 specification of 8.228-8.232 inches to indicate their variance from the standard radius. It should be noted that the tolerance for the lining radius is the same as that for the lining radius fixture (±0.002 inch). The mean and standard deviation are calculated for each lining set to determine uniformity of the cut. A second group of mean and standard deviation values are calculated to compare each individual measurement location radii, for all of the units selected for the initial conditioning burnish series, to indicate the tolerance of the "cut" for each of the 18 locations. Both of these groups of calculations are used to identify the repeatability of the cutting process.

Once these radius measurements are tabulated, a dial caliper is used to measure the thickness of both the lining and the shoe at 12 locations on each shoe assembly. Each measurement is made 1-1/2 inches in from the outer edge (see Figure 4.6) along both sides of the shoe (the caliper cannot measure the center of the shoe due to its center web design). The measurements are made more repeatable by indexing indentations dimpled into the rear of the shoe castings. This establishes a baseline thickness reference for comparing lining loss from abrasion during additional testing.

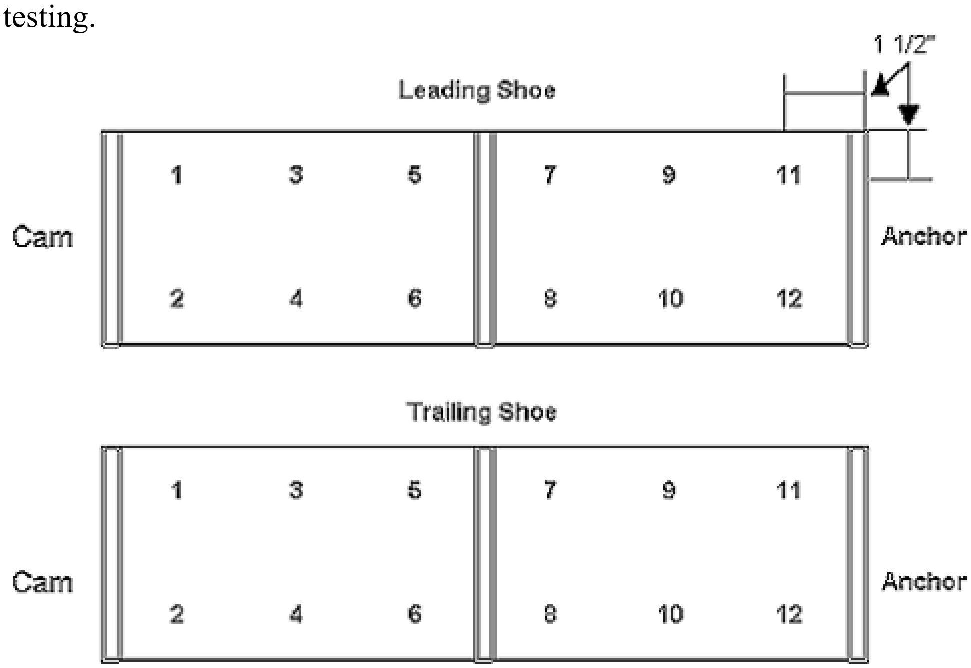


FIGURE 4.6 - Thickness Measurement Locations on Each Shoe

Every time a new shoe set is tested on the dynamometer, both “pre-test” and “post-test” thickness measurements are made. The difference in the pre- and post-test readings will indicate the amount of wear that occurred during that test series. For each subsequent test on the same linings, only the post-test measurements are made, as the initial values are simply transcribed from the post-test measurements made at the end of the previous test.

Additionally, the shoe assemblies are weighed both pre-test and post-test for the initial setup, to indicate the total bulk of the lining material that abrades during the first test. For each subsequent test on the same linings, only the post-test measurements are made, as the initial values are simply transcribed from the post-test measurements that were made at the end of the previous test. The drum is also weighed at the same intervals to track its loss of material.

A final radius measurement was made on the shoe assemblies at the end of the test series to indicate the amount of lining material lost during the tests. The measurements are listed in Appendix B, Tables B.3 and B.4.

4.3.4 Installation and Conditioning on Dynamometer

In previous J1802 research it was found that the brake lining effectiveness ratings were affected by the conditioning of the brake linings and drums. As part of the first round-robin of testing discussed in Section 1.2, Background, the brake lining and drum were conditioned prior to being sent out to the different test sites for evaluation. This conditioning process was performed to stabilize the lining to minimize the confounding effect of the brake conditioning in differences seen between test labs. To evaluate test fixture differences in the current study, properly stabilized brake lining/drum combinations were necessary. To achieve proper stabilization, a full J1802 test procedure was performed on each brake setup.

Each brake setup was configured according to the specification of the SAE J1802 procedure. One variance was that a Webb 69802 drum was substituted for the prescribed Gunite drum. Prior to the first round-robin test, several of the Gunite drums failed during dynamometer tests due to metallurgical deficiencies, and the HDBMC recommended the Webb substitute. The drums used for this test series were new units from the original group of Webb drums tested in the round-robin tests. The VRTC provided Rockwell stub axle and hub were used for all fixtures tested. A new drum was used for each brake set, then maintained with that brake set for the remainder of the test series. New bronze bushings were used with each shoe set. The cams and rollers were lubricated prior to each test. Figure 4.7 shows the left wheel convention used for the tests (the top cover of the cooling tunnel is removed for setup purposes). The 10,000 pound-foot torque measuring apparatus is mounted in the right hand pedestal base. The thermocouple array signals are passed from the drum through slip rings on the outside of the left pillow block bearing.

Eight sets of linings were "conditioned" on the VRTC fixture using the J1802 test procedures. The shoe assemblies and the drum were each weighed in the pre-test condition, then installed on the dynamometer, and adjusted. The brake was pre-heated with a few constant torque stops as prescribed in J1802. The conditioning burnish cycle began with 200 normal temperature braking stops from 37 to 0 mph at 392 degrees Fahrenheit initial braking temperature. Each burnish stop was performed at a constant torque of 9.8 fps^2 (feet per second per second or 0.3 g deceleration). Next, nine constant pressure stops were made, with each of the nine stops at increased pressure increments from 15 to 55 psi, in 5 psi steps. This sweep of pressures was repeated one more time for a total of 18 consecutive effectiveness stops. These "normal temperature effectiveness" stops were initiated at an initial braking temperature of 212 degrees F with the speed at 47 mph. After the brake cooled, the slack adjuster was manually re-adjusted to the proper alignment angle and chamber stroke lengths.

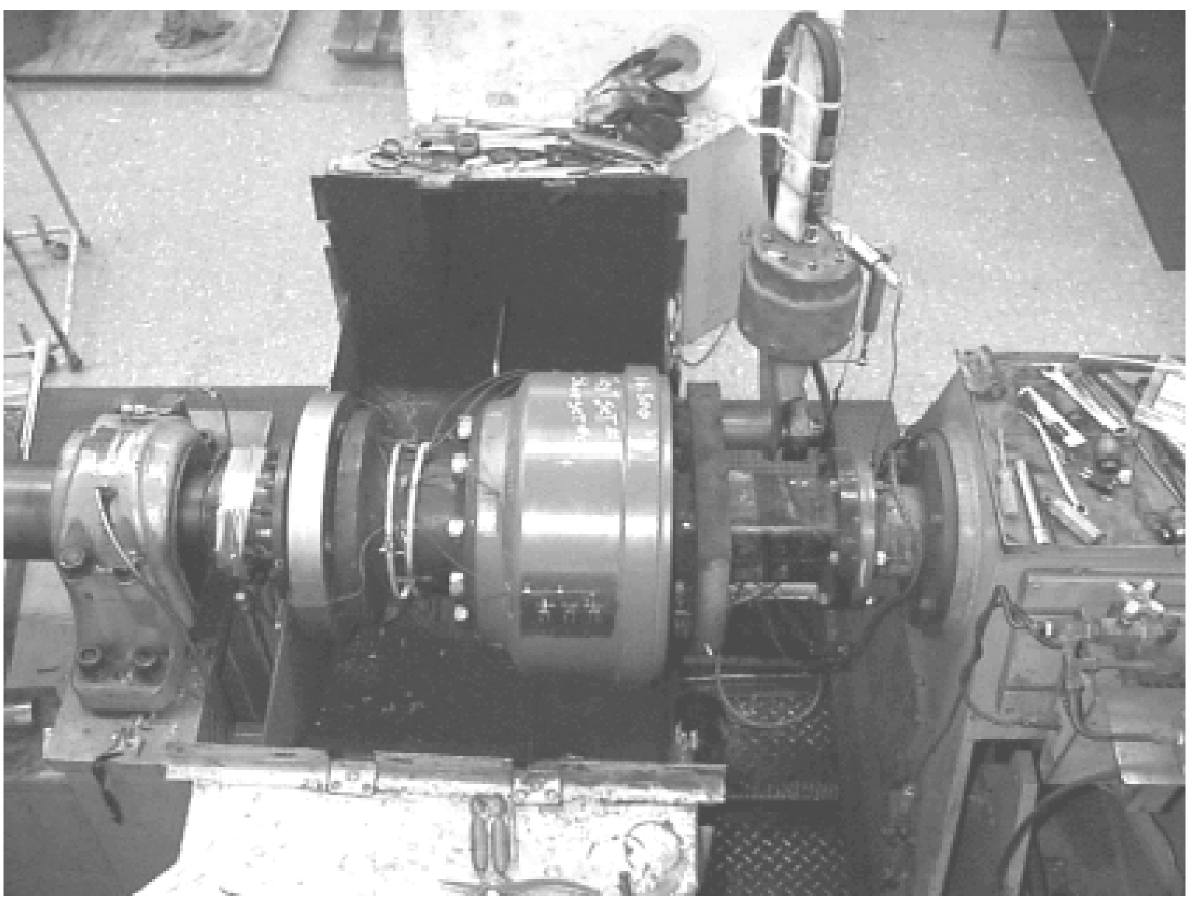


FIGURE 4.7 – Brake Installation on Dynamometer

After pre-heating again, the series continued with a high temperature "hot" burnish procedure beginning with 200 stops from 37 to 0 mph at 572 deg F initial braking temperature. The constant torque deceleration rate was again controlled at 9.8 fps^2. A cool curve was run at a speed of 5 mph with the brake released to determine the brake drum cooling characteristics. After pre-heating, a final high temperature effectiveness test series completed the conditioning, with two sweeps of the nine constant pressure ranges (the same as used in the normal temperature effect) and the same 47 mph initial speed, but at an initial braking temperature of 572 deg F.

After the assembly cooled, the shoe assemblies and the drum were removed from the dynamometer, inspected for percent of lining surface contact, weighed in the post-test condition, then set aside with the mating drum for comparative testing at a later date.

This conditioning process was repeated for eight sets of linings. The other four shoe sets were maintained as alternate units in the cut to radius, but not tested, status. Each brake set that was conditioned was prepared using this same routine. All sets run on the VRTC fixture for the initial conditioning resulted in 100 percent lining contact, so no contact pattern photographs were made.

4.3.5 Fixture Comparison Test

The Carlisle and the Abex fixtures were chosen for the comparative dynamometer tests. As stated previously, these fixtures were selected because they were the most complete sets sent to VRTC for evaluation. The VRTC fixture was used to condition the brake lining/drum combinations.

Due to time constraints and the additional strain gaged camshaft on the Abex fixture, all of the linings were tested on the Carlisle fixture while the data reduction program was being modified to accommodate the extra camshaft torque data channel. The linings were chosen at random from the group of pre-conditioned units. Two sets of each type of lining were tested. Both the shoe assemblies and the drum were weighed in the pre- and post-test modes, and the combined shoe and lining thickness locations were measured. The first BrakePro lining set run (1A) was interrupted by a program glitch and the run was aborted. The rest of the series was completed just to verify the operation of the program. An additional test (1B) was run to replace the aborted test. Upon completion of the Carlisle fixture set, the Abex fixture was installed in the dynamometer and the same lining sets run again, but in a new random order.

The braking sequence procedure followed was the same as used during the VRTC normal temperature conditioning series, with 200 constant torque stops from 37 mph at 392 deg F initial braking temperature and 18 constant pressure effectiveness stops sweeping twice from 15 to 55 psi in 5 psi steps from 47 mph at 212 deg F initial braking temperature.

Contact pattern photographs were made after all testing was complete and they showed 100 percent lining contact.

4.4 J1802 Comparison Testing Results

The brake shoe and drum measurement values are given in Section 4.4.1. The results from the normal and high temperature brake effectiveness/conditioning runs performed with the VRTC test fixture will be discussed in Section 4.4.2. This will be followed in Section 4.4.3 by the normal temperature effectiveness comparison test results using the Carlisle and Abex test fixtures. A comparison of the "conditioning" effectiveness results found with the VRTC fixture will be compared to those found with the Abex and Carlisle fixtures in Section 4.4.4. The Abex input torque was determined using two methods as described in Section 4.2.4. The results for the two methods will be discussed in Section 4.4.5.

4.4.1 Brake Shoe and Drum Measurement Values

The pre-test brake shoe arch measurements collected using the VRTC Lining Radius Fixture for each brake shoe set are given in Tables 4.2 and 4.3 for the leading and trailing brake shoes respectively. The mean and standard deviation for each radius measurement are given for each measurement position (see Figure 4.5) and for each shoe. The measurement position mean and standard deviation values are given on the left side of the tables and the individual brake shoe values are given at the bottom of the tables.

TABLE 4.2 - Brake Shoe Radius Measurements: Leading Brake Shoe

	Set 01	Set 02	Set 03	Set 04	Set 07	Set 08	Set 09	Set 10	Mean	Std. Dev.
1	8.184	8.162	8.153	8.153	8.159	8.163	8.164	8.180	8.165	0.011
2	8.167	8.138	8.132	8.133	8.138	8.138	8.138	8.162	8.143	0.013
3	8.156	8.130	8.127	8.125	8.132	8.126	8.130	8.155	8.135	0.012
4	8.159	8.131	8.128	8.127	8.132	8.126	8.131	8.155	8.136	0.012
5	8.168	8.148	8.146	8.143	8.148	8.146	8.146	8.164	8.151	0.009
6	8.190	8.179	8.183	8.180	8.183	8.179	8.178	8.186	8.182	0.004
7	8.194	8.171	8.164	8.171	8.173	8.178	8.164	8.191	8.176	0.011
8	8.180	8.148	8.150	8.150	8.151	8.156	8.151	8.178	8.158	0.012
9	8.175	8.166	8.147	8.145	8.146	8.150	8.144	8.173	8.156	0.012
10	8.175	8.166	8.148	8.146	8.146	8.150	8.144	8.172	8.156	0.012
11	8.185	8.153	8.163	8.163	8.161	8.163	8.160	8.183	8.166	0.011
12	8.206	8.186	8.196	8.193	8.191	8.192	8.191	8.203	8.195	0.006
13	8.207	8.183	8.183	8.188	8.190	8.194	8.185	8.203	8.192	0.009
14	8.192	8.163	8.168	8.173	8.170	8.178	8.166	8.193	8.175	0.011
15	8.191	8.152	8.166	8.170	8.163	8.173	8.161	8.192	8.171	0.013
16	8.193	8.154	8.168	8.170	8.163	8.173	8.162	8.193	8.172	0.013
17	8.204	8.170	8.184	8.185	8.176	8.186	8.178	8.204	8.186	0.012
18	8.221	8.198	8.213	8.208	8.192	8.208	8.204	8.219	8.208	0.009
Mean	8.186	8.161	8.162	8.162	8.162	8.166	8.161	8.184		
Std. Dev.	0.017	0.019	0.024	0.024	0.020	0.023	0.021	0.018		

TABLE 4.3 - Brake Shoe Radius Measurements: Trailing Brake Shoe

	Set 01	Set 02	Set 03	Set 04	Set 07	Set 08	Set 09	Set 10	Mean	Std. Dev.
1	8.153	8.185	8.169	8.185	8.183	8.178	8.181	8.145	8.172	0.014
2	8.134	8.166	8.159	8.186	8.176	8.158	8.162	8.121	8.158	0.020
3	8.126	8.156	8.158	8.156	8.158	8.150	8.155	8.118	8.147	0.015
4	8.127	8.156	8.159	8.156	8.158	8.150	8.156	8.124	8.148	0.013
5	8.148	8.167	8.168	8.189	8.168	8.161	8.167	8.143	8.164	0.013
6	8.172	8.187	8.195	8.185	8.188	8.185	8.190	8.178	8.185	0.007
7	8.166	8.205	8.186	8.190	8.198	8.191	8.190	8.164	8.186	0.013
8	8.147	8.187	8.173	8.175	8.181	8.175	8.175	8.145	8.170	0.014
9	8.143	8.173	8.171	8.169	8.174	8.167	8.170	8.143	8.164	0.012
10	8.144	8.173	8.172	8.169	8.173	8.168	8.172	8.143	8.164	0.012
11	8.161	8.183	8.183	8.179	8.180	8.179	8.183	8.161	8.176	0.009
12	8.196	8.202	8.204	8.199	8.198	8.199	8.203	8.191	8.199	0.004
13	8.183	8.205	8.207	8.197	8.212	8.217	8.201	8.187	8.201	0.011
14	8.169	8.195	8.197	8.189	8.198	8.196	8.190	8.173	8.188	0.011
15	8.168	8.193	8.195	8.189	8.192	8.194	8.189	8.171	8.186	0.010
16	8.169	8.193	8.194	8.189	8.191	8.195	8.190	8.170	8.186	0.010
17	8.184	8.203	8.201	8.201	8.194	8.202	8.197	8.184	8.195	0.007
18	8.210	8.219	8.215	8.221	8.208	8.218	8.219	8.208	8.215	0.005
Mean	8.161	8.186	8.184	8.185	8.185	8.182	8.130	8.159		
Std. Dev.	0.023	0.018	0.018	0.016	0.015	0.021	0.017	0.026		

Combining the leading and trailing brake shoe measurements; by measurement position, the mean values ranged from 8.135 to 8.215 inches with standard deviations ranging from 0.004 to 0.021 inch. By individual brake shoe, the mean values ranged from 8.130 to 8.186 inches with standard deviations ranging from 0.015 to 0.026 inch. It should be noted that the average values are less than the J1802 specified arch radius values of 8.228 to 8.232 inches. The average values also have a greater variability than that specified by J1802. It is not known what the effect of having a slightly smaller radius than that specified might be on J1802 effectiveness ratings. Since the linings were tested in a similar manner on both fixtures, the authors believe that the smaller radius values do not substantially affect the comparison test results.

A single brake drum diameter measurement was made pre-test on each drum and all were found to be 16.50 inches.

Each of the linings was conditioned by running the J1802 normal and high temperature procedures on the VRTC test fixture. Two linings from each manufacturer were then evaluated using the normal temperature procedures with the Carlisle and the Abex fixtures.

The average measured lining wear (change in lining thickness) after the testing conducted on each fixture is given in Table 4.4. These values are the average of the twelve measured values shown in Figure 4.6. Pre- and post-test measurements were made. The post-test measurements were subtracted from the pre-test measurements and then divided by the pre-test measurements. The twelve percentage changes were then averaged to give the numbers in Table 4.4. The individual measurements are given in Appendix B. The percentage change is quite small. The leading shoe for BrakePro lining 01 and the trailing shoe BrakePro lining 02 had relatively larger wear. The wear for testing on the Carlisle and Abex fixture was generally less than that for the VRTC fixture. This is probably due to a greater number of tests being performed on the VRTC fixture (normal and high temperature).

TABLE 4.4 - Average Measured Brake Lining Wear - Average Percentage Change in Lining Thickness Calculated for the Twelve Measured Positions

Manufacturer	Lining Number	Average Change in Lining Thickness (% decrease)					
		Leading			Trailing		
		VRTC	Carlisle	Abex	VRTC	Carlisle	Abex
BrakePro	01	1.3	–	–	0.6	–	–
	02	0.8	–	–	1.4	–	–
	03	0.7	0.4	0.5	0.9	0.4	0.4
	04	0.3	0.4	0.4	0.4	0.3	0.4
Haldex	07	0.3	0.2	0.3	0.3	0.1	0.2
	08	0.0	–	–	0.2	–	--
	09	0.0	–	–	0.1	–	–
	10	0.5	0.3	0.3	0.2	0.2	0.1

The brake shoe weight change after the testing conducted on each fixture is given in Table 4.5. Pre- and post-test measurements were made. The post-test measurements were subtracted from the pre-test measurements and then divided by the pre-test measurements. The individual measurements are given in Appendix B. The percentage change is quite small. As was the case for wear, the brake shoe weight change for testing on the Carlisle and Abex fixture was generally less than that for the conditioning stops on the VRTC fixture. The one exception to this rule was the Haldex lining 07.

TABLE 4.5 - Brake Shoe Weight Change

Manufacturer	Lining Number	Brake Shoe Weight Change (% decrease)					
		Leading			Trailing		
		VRTC	Carlisle	Abex	VRTC	Carlisle	Abex
BrakePro	01	0.8	–	–	0.4	–	–
	02	0.8	–	–	0.4	–	–
	03	0.8	0.0	0.4	0.8	0.0	0.4
	04	0.8	0.0	0.4	0.8	0.4	0.4
Haldex	07	0.0	0.4	0.4	0.4	0.0	0.4
	08	0.0	–	–	0.4	–	--
	09	–	–	–	0.4	–	--
	10	0.4	0.4	0.4	0.4	0.4	0.4

The drum weight change after the testing conducted on each fixture is given in Table 4.6. Pre- and post-test measurements were made. The post-test measurements were subtracted from the pre-test measurements and then divided by the pre-test measurements. The individual measurements are given in Appendix B. The percentage change in drum weight is quite small. As was the case for wear and brake shoe weight change, the drum weight change for testing on the Carlisle and Abex fixture was generally less than that for the VRTC fixture. Again this was probably due to a greater number of conditioning stops performed on the VRTC fixture.

TABLE 4.6 - Drum Weight Change

Manufacturer	Lining Number	Drum Weight Change (% decrease)		
		VRTC	Carlisle	Abex
BrakePro	01	0.2	--	--
	02	0.2	No data	--
	03	0.1	0.0	0.0
	04	0.2	0.0	0.0
Haldex	07	0.1	0.0	0.0
	08	0.1	--	--
	09	0.1	--	--
	10	0.1	0.0	0.1

After all testing was complete, the lining arches were re-measured using the VRTC Lining Radius Fixture. The average change in radius (lining wear) for the leading and trailing shoes of the linings tested on the Carlisle and Abex fixtures (Linings 03, 04, 07, and 10) are given in Table 4.7. These average values are calculated using the difference between the pre- and post-test measurements for all 18 locations. All of the measurements are given in Appendix B. The average lining wear for the BrakePro linings (03 and 04) was greater than that for the Haldex linings (07 and 10). Average lining wear values for each lining brand were very similar, i.e., the two BrakePro linings had very similar average lining wear.

TABLE 4.7 - Average Lining Wear

Lining Position	Average Lining Wear (in)			
	Lining 03	Lining 04	Lining 07	Lining 10
Leading	0.018	0.015	0.010	0.010
Trailing	0.018	0.020	0.005	0.004

4.4.2 Results from Conditioning Tests Performed with the VRTC Test Fixture

Four brake linings from each of the two manufacturers (BrakePro and Haldex) were conditioned by performing J1802 normal temperature and high temperature effectiveness test series on each lining. The details for how this "conditioning" procedure was performed are given in Section 4.3.4. A linear regression between the input and output torque values was performed for both effectiveness test series. The slope of the linear regression line is a measure of the effectiveness of brake lining material.

The normal temperature effectiveness values for the conditioning tests are given in Figure 4.8. Lining 01 was tested twice due to problems that occurred during the 200 initial normal temperature braking stops. The dynamometer controller created a pause during the tests that allowed the brake temperatures to cool below the desired temperature range. The entire test procedure was repeated for this lining. The initial test is labeled 1A and the second test is labeled 1B.

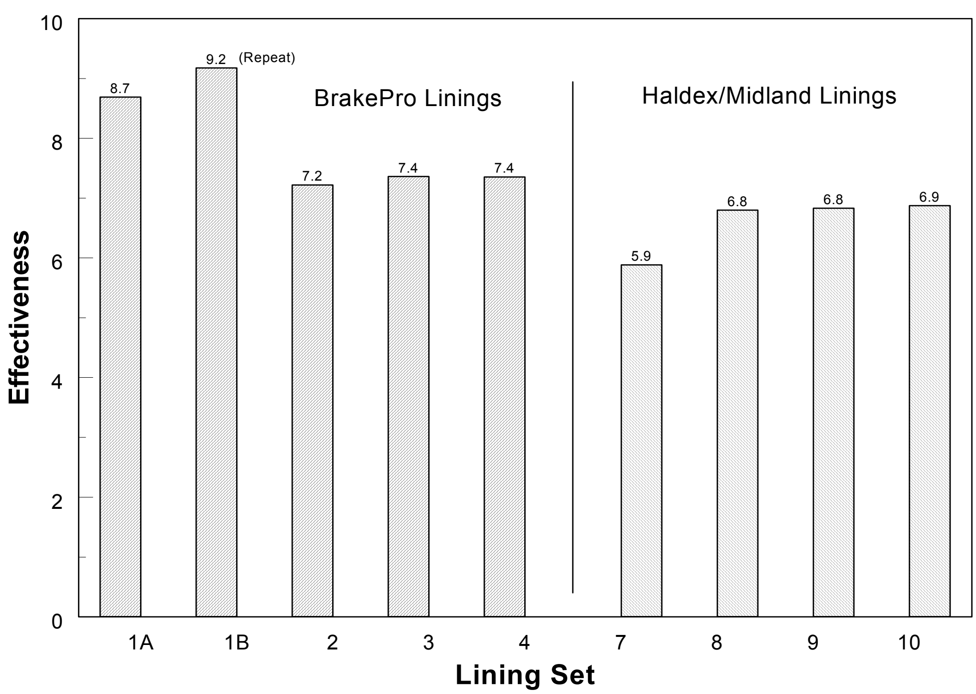


FIGURE 4.8 – Normal Temperature Effectiveness – VRTC Test Fixture - Lining Conditioning Tests

Both the BrakePro and Haldex linings had three normal temperature effectiveness values that were very similar and one that was not. BrakePro Lining 01 had an effectiveness value that was higher than that for the other BrakePro linings and Haldex Lining 07 had a lower effectiveness value than the other Haldex linings. The BrakePro Lining 01 effectiveness values may have been higher due to cooling (described in previous paragraph) that occurred during the initial 200 stops for 1A. The 1B effectiveness value is higher than that for 1A. This is consistent with results that will be discussed in Section 4.4.3. An examination of the lining wear results presented in Section 4.4.1 does not give any insight to the reasons for the variability seen for Linings 01 and 07.

The high temperature effectiveness values are given in Figure 4.9. As was the case for the normal temperature effectiveness values, the high temperature effectiveness values for BrakePro Lining 01 are higher than those found for the other BrakePro linings. The high temperature effectiveness value for 1B was higher than that for 1A as well. The Haldex linings had very similar high temperature effectiveness values for all four of the linings tested. The Haldex high temperature effectiveness values were lower than those found for the BrakePro lining.

4.4.3 Results from Comparison Tests Performed with the Abex and Carlisle Test Fixtures

The Abex and Carlisle test fixtures were evaluated using the normal temperature J1802 procedures specified in Section 4.3.5. Two sample brake linings from two manufacturers (BrakePro and Haldex) were tested on each fixture. These linings were selected randomly and blindly, i.e., not knowing the effectiveness results from the conditioning tests performed with the VRTC test fixture that were given in Section 4.4.2. BrakePro Linings 02 and 04 were initially selected, but the testing for Lining 02 was aborted after 8 out of 18 effectiveness tests were performed. Lining 03 was evaluated to replace Lining 02. Linings 02, 03, and 04 had very similar effectiveness values for the conditioning tests. Haldex Linings 07 and 10 were selected for testing. These two linings had relatively different normal temperature effectiveness values.

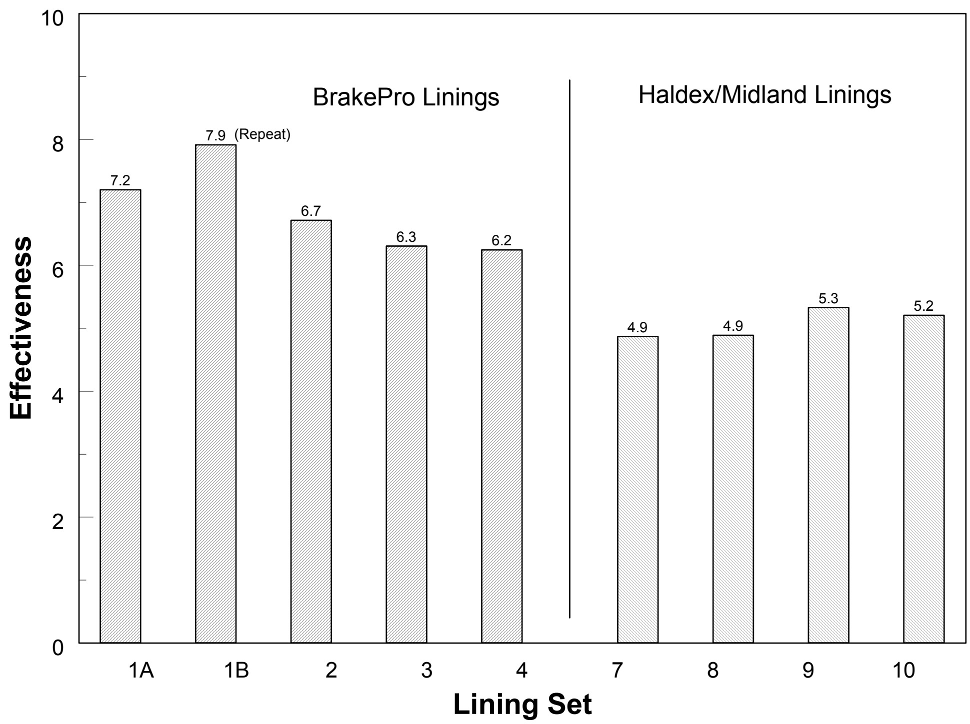


FIGURE 4.9 – High Temperature Effectiveness – VRTC Test Fixture - Lining Conditioning Tests

The input and output torque values were monitored and a linear regression of the data was performed. The slope of the linear regression line is a measure of the effectiveness of the brake lining material.

The effectiveness values for each test condition are given in Table 4.8. The percent difference values are given also. The percent difference is determined by subtracting the two values and then dividing by the average of the two values. Percent difference values are given for the different lining material values and for the same lining material measured by the two different test fixtures.

TABLE 4.8 - Calculated Effectiveness Values for Comparison Tests

Lining	Effectiveness Values		Percent Difference
	Abex	Carlisle	
BrakePro 03	8.1	7.9	2.5
BrakePro 04	7.9	8.1	2.5
Percent Difference	2.5	2.5	
Haldex 07	6.5	7.2	10.2
Haldex 10	7.7	7.8	1.3
Percent Difference	16.9	8.0	

The percent difference values between the Abex and Carlisle test fixtures ranged from 1.3 to 10.2 percent. These percentages are much lower than those found in the seven test site round-robin series discussed in Chapter 1 (see Figure 1.2). While this is a very limited sample of data points, it does suggest that a lot of the variability may come from sources other than the test fixtures (dynamometer, operator, slightly different set-up procedures, etc.).

The percent difference values for the same material brand using the same test fixture range from 2.5 to 16.9 percent. The BrakePro lining material had much less variability than the Haldex lining. The Haldex 07/Abex test fixture combination produced what appears to be an outlier relative to the other data. More data would have to be collected to determine if the percent difference for this test is more indicative of the variability in testing or whether it is truly an outlier. It should be noted that the BrakePro linings selected for further evaluation were those that had the most similar effectiveness values found on the VRTC fixture while the Haldex linings selected were the most dissimilar.

The output torque versus input torque curves for each individual brake lining are given in Figures 4.10 through 4.13. The test and linear regression results from each fixture are displayed. The Abex fixture results have open symbols with a dashed line for the regression and the Carlisle fixture results have solid symbols with a solid line. The linear regressions include both the increasing and decreasing torque values. The Abex fixture generally measured lower output torque values than those found with the Carlisle fixture. Despite these lower values and as discussed previously, the linear regression slope values measured with each test fixture were very similar except for the Haldex 07 lining (Figure 4.12).

The same data are plotted in a slightly different manner in Figures 4.14 through 4.17. In these figures the same lining manufacturer/test fixture combinations are plotted as pairs. The BrakePro 03 and 04 lining output torque values were very similar whether they were measured on the Abex fixture or the Carlisle fixture (Figures 4.14 and 4.15 respectively). The Haldex 07 lining had lower output torque values than the Haldex 10 for both of the test fixtures (Figures 4.16 and 4.17). Since both fixtures produced this similar result, it appears that the two Haldex lining materials had different properties. It is not clear whether this was due to lining material differences, the brake conditioning procedure, or some other influence.

In summary, the test matrix was designed to reduce the variability in test results due to dynamometer, operator, setup procedure differences, and other unforeseen potential sources. Having a single operator perform testing with a single dynamometer using two different test fixtures produced results that had far less variability than those found in the seven test site round-robin series discussed in Chapter 1 (see Figure 1.2). While only a very limited number of tests were performed, the results suggest that much of the variability found in the round-robin may have come from sources other than the test fixtures (dynamometer, operator, slightly different set-up procedures, brake lining and/or brake drum material differences, etc.).

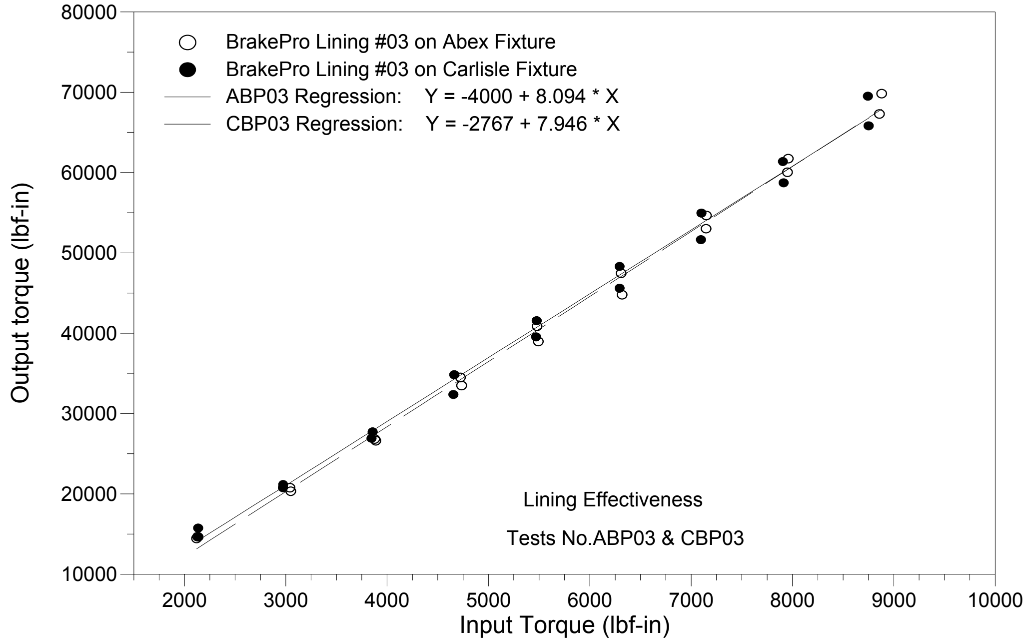


FIGURE 4.10 - BrakePro 03 Lining Effectiveness Values for the Abex and Carlisle Fixtures

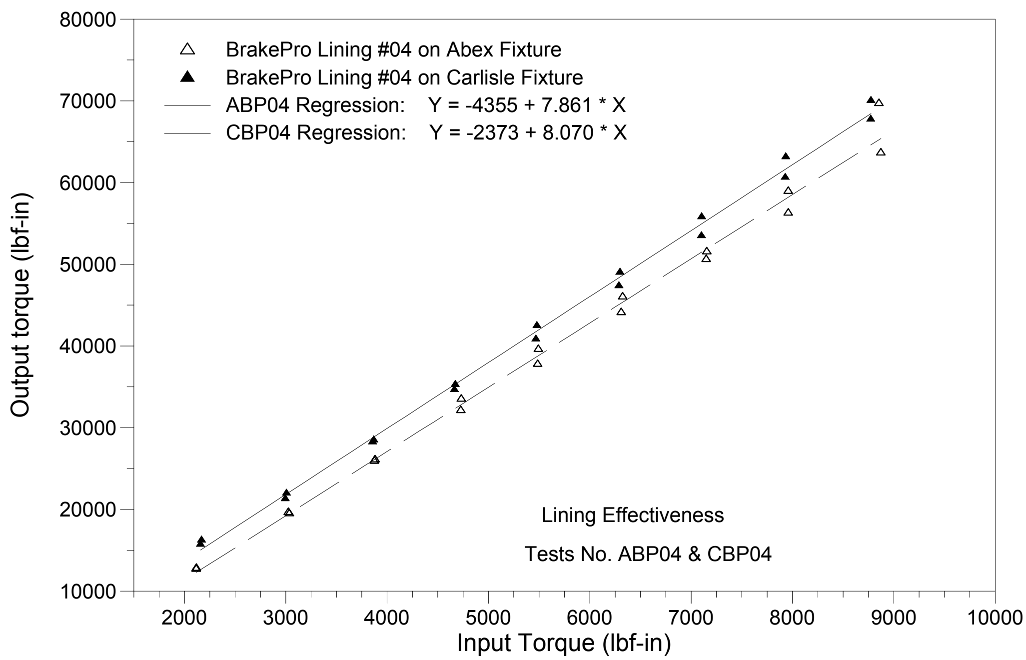


FIGURE 4.11 - BrakePro 04 Lining Effectiveness Values for the Abex and Carlisle Fixtures

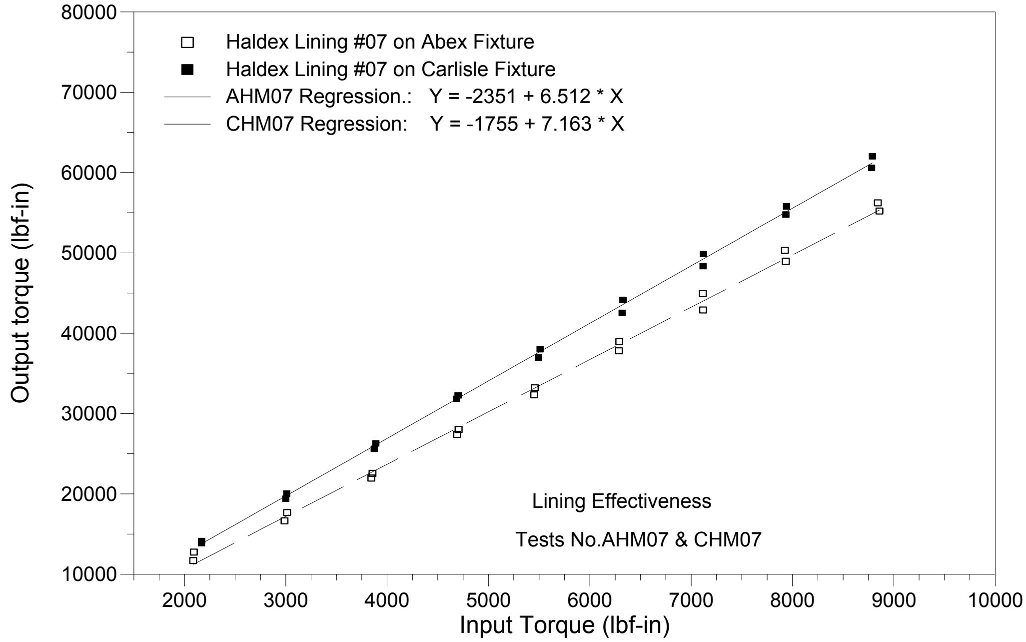


FIGURE 4.12 - Haldex 07 Lining Effectiveness Values for the Abex and Carlisle Fixtures

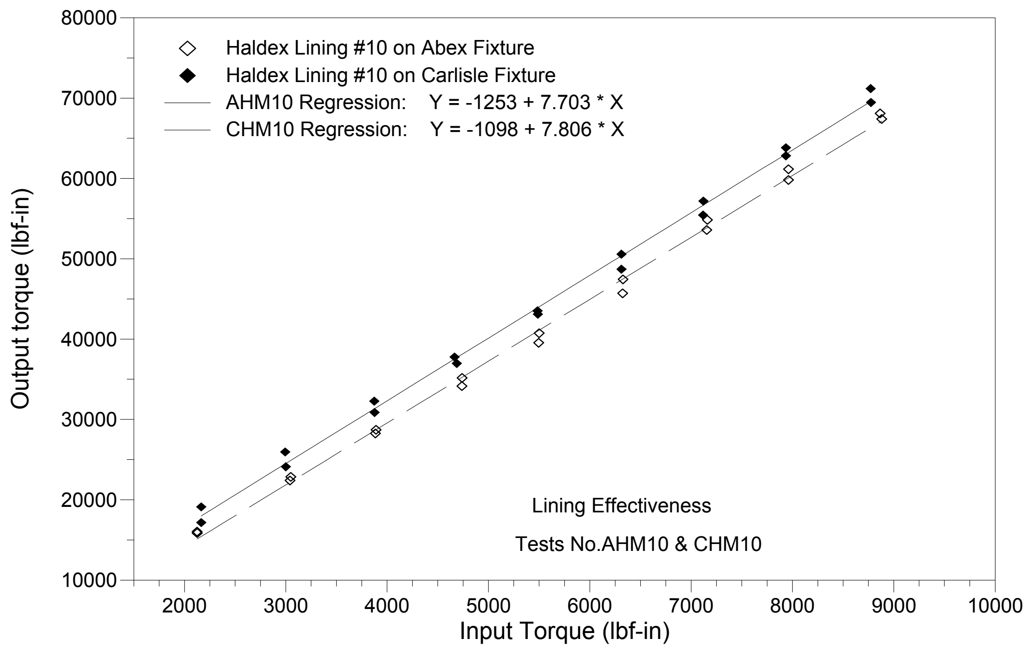


FIGURE 4.13 - Haldex 10 Lining Effectiveness Values for the Abex and Carlisle Fixtures

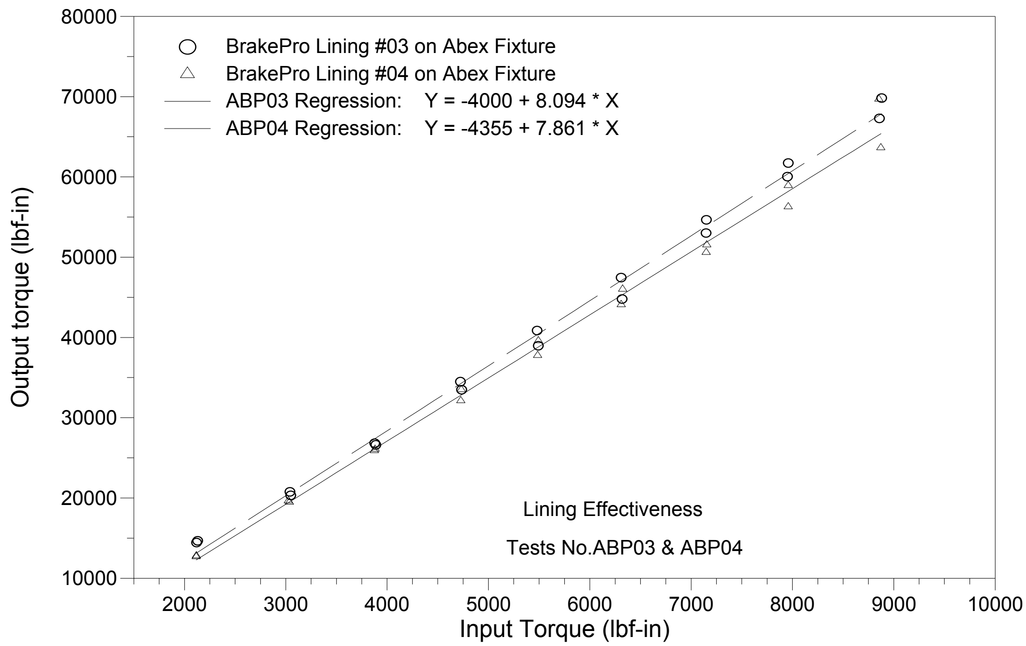


FIGURE 4.14 - BrakePro Lining Effectiveness Values for the Abex Fixture

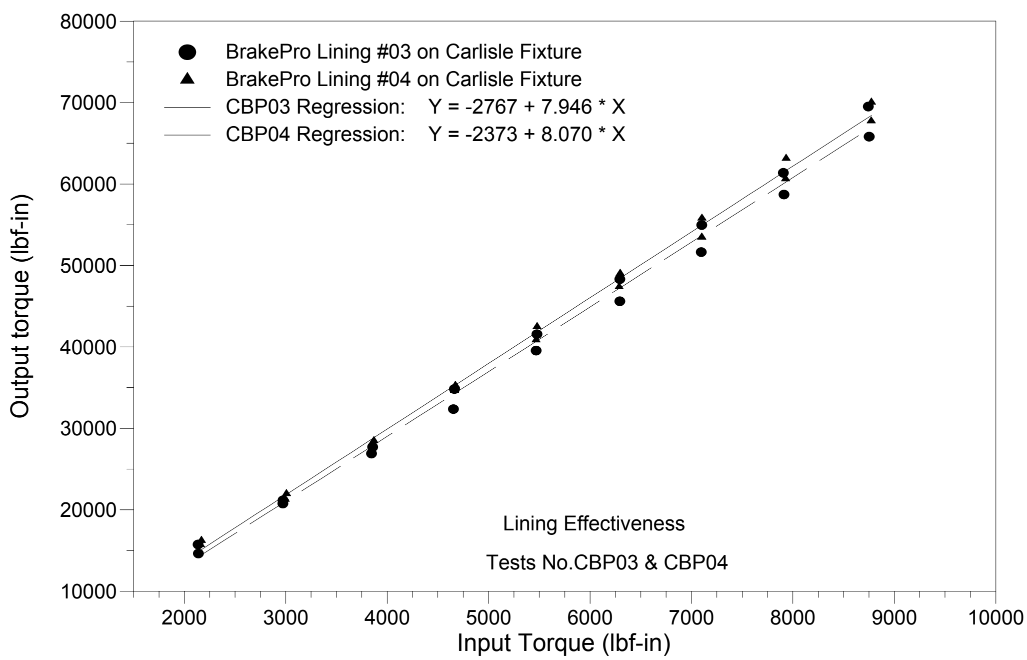


FIGURE 4.15 - BrakePro Lining Effectiveness Values for the Carlisle Fixture

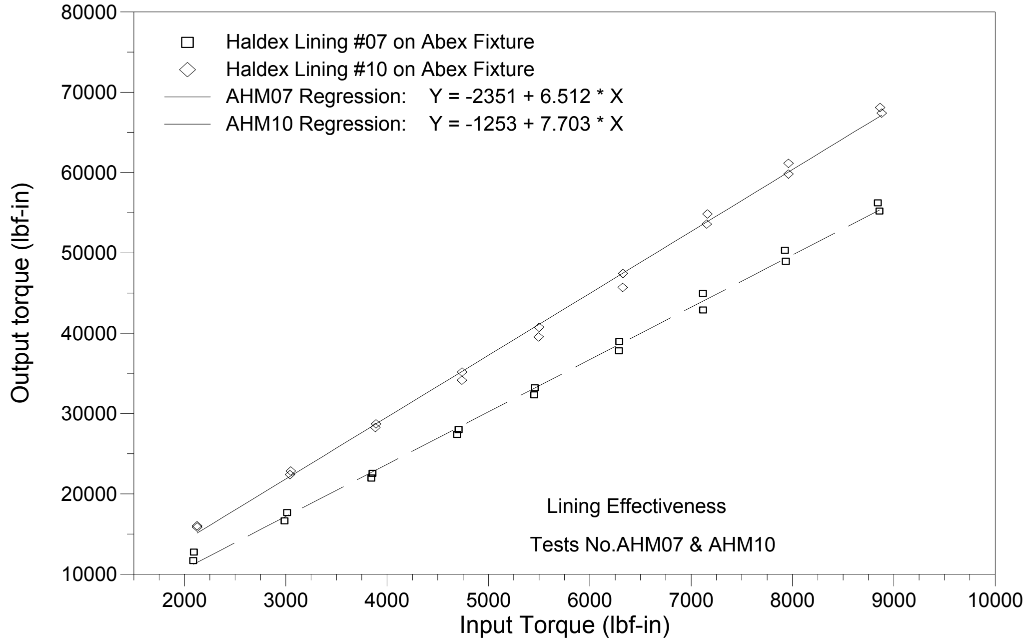


FIGURE 4.16 - Haldex Lining Effectiveness Values for the Abex Fixture

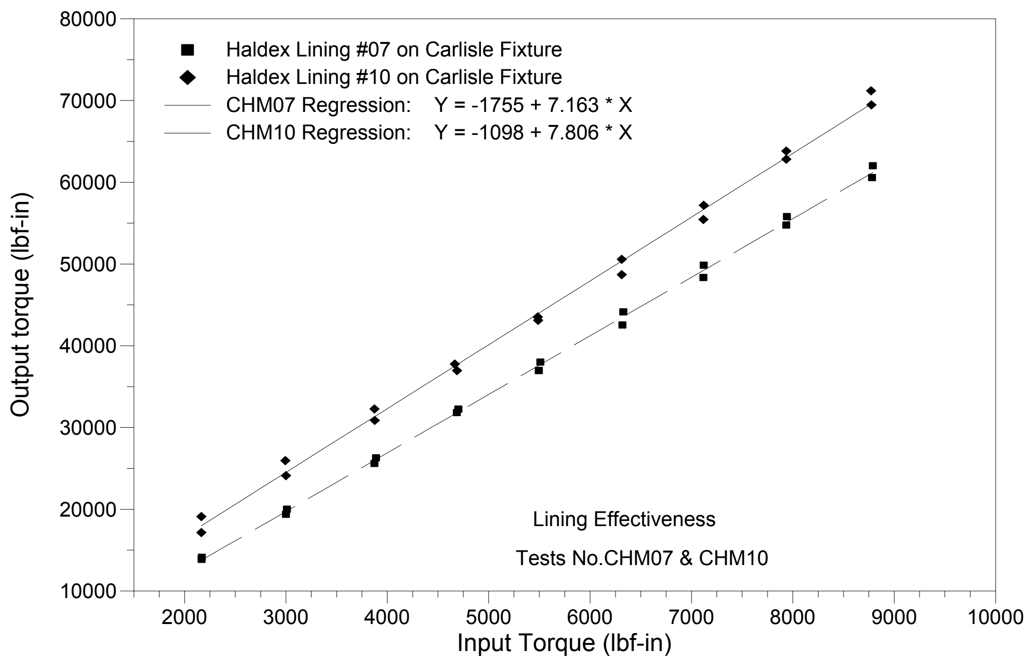


FIGURE 4.17 - Haldex Lining Effectiveness Values for the Carlisle Fixture

4.4.4 Comparison of "Conditioning" Tests Performed with the VRTC Test Fixture and the Tests Performed with the Abex and Carlisle Test Fixtures

The VRTC normal temperature conditioning test effectiveness values and the Abex and Carlisle normal temperature effectiveness values for all of the brake linings are plotted in Figure 4.18. The effectiveness value for BrakePro Lining 02/Carlisle Fixture is calculated based on only 8 of 18 tests. The effectiveness values for the Abex and Carlisle fixtures are higher than those for the VRTC fixture. This effect was also seen on BrakePro Lining 01 for the two conditioning runs on the VRTC test fixture (1A and 1B). The same is also true for the 1A and 1B tests.

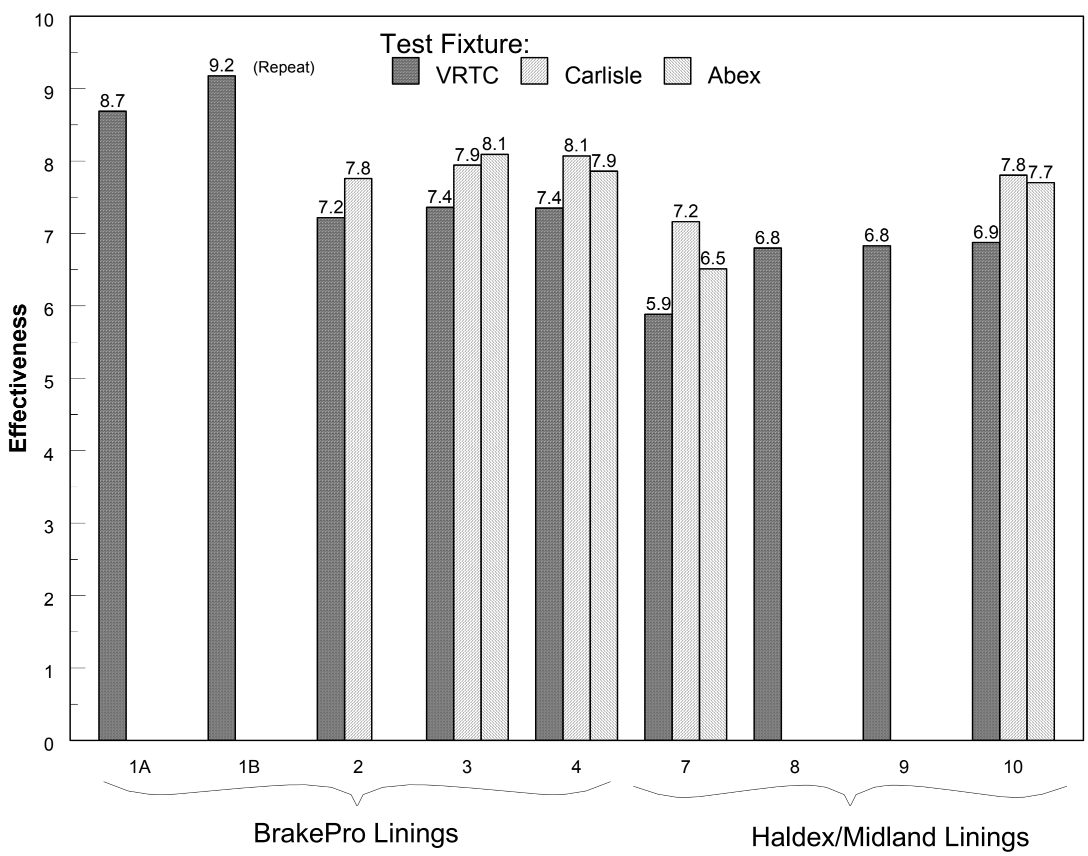


FIGURE 4.18 - Normal Temperature Effectiveness Values of All Conditioning and Test Runs

The VRTC fixture conditioning test effectiveness values are compared to those found using the Abex and Carlisle fixtures in Table 4.9. The percent difference values are also given. The percent difference is determined by subtracting the two values and then dividing by the average of the two values. Percent difference values are given for VRTC versus Abex and VRTC versus Carlisle test fixture effectiveness values for each lining material tested. The percent difference for each lining brand tested on each fixture is also given, e.g., BrakePro 03 and 04 tested on the VRTC fixture.

The percent difference values between the VRTC and Abex test fixtures ranged from 6.5 to 11.0 percent while those for the VRTC and Carlisle test fixtures ranged from 6.5 to 19.8 percent. These percentages are higher than those found for the differences between the Abex and Carlisle fixtures (1.3 to 10.2 percent).

TABLE 4.9 - Comparison of VRTC Test Fixture Conditioning Test Effectiveness Values to those Found with the Abex and Carlisle Test Fixtures

Lining	VRTC	Abex		Carlisle	
	Effectiveness	Effectiveness	Percent Difference	Effectiveness	Percent Difference
BrakePro 03	7.4	8.1	9.0	7.9	6.5
BrakePro 04	7.4	7.9	6.5	8.1	9.0
Percent Difference	0.0	2.5		2.5	
Haldex 07	5.9	6.5	9.7	7.2	19.8
Haldex 10	6.9	7.7	11.0	7.8	12.2
Percent Difference	15.6	16.9		8.0	

The results given in Figure 4.18 and Table 4.9 are not surprising. A probable reason for this difference is that a set of high temperature conditioning tests was run between the VRTC normal temperature conditioning tests and the normal temperature tests using the Abex and Carlisle test fixtures. The reason for conducting the conditioning tests was to make sure the combination of the brake lining and drum was producing stable results that would hopefully not fluctuate during the comparison testing. Verifying that the brake lining/drum combination was stable after the conditioning tests probably should have been performed by conducting another set of normal temperature tests (burnish and effectiveness tests) using the VRTC test fixture. If the effectiveness values did not fluctuate and were similar to those obtained with the Abex and Carlisle test fixtures, then it could be better assumed that the brake lining/drum combination was producing stable results. The fact that the results are very similar for the Abex and Carlisle fixtures suggests that the brake lining/drum combinations were producing stable results, with the one possible exception being the Haldex 07 lining. These results suggest that a longer or higher temperature burnish may be required for the lining/drum to reach a stable condition prior to effectiveness testing being conducted.

The percent difference values for the same material brand using the same fixture range from 0.0 to 16.9 percent. As was found in Section 4.4.3, the BrakePro lining material had much less variability than the Haldex lining. It should be noted that only two of the four lining materials (from each brake supplier) conditioned using the VRTC test fixture are shown in Table 4.9. Figure 4.18 shows that the BrakePro linings had greater variability on the VRTC fixture than did the Haldex linings. This is true even if the BrakePro 1B results are omitted. As stated in Section 4.4.3, the BrakePro linings selected (randomly) for further evaluation had the most similar effectiveness values measured on the VRTC fixture while the Haldex linings selected (randomly) were the most dissimilar.

4.4.5 Input Torque Measurement Results

The Abex test fixture had strain gages applied to the cam in a pattern that was designed to measure the input torque directly. Measuring the torque directly should be easier to perform than the current method of creating a lookup table of force versus stroke for the service chamber. Calibration of the cam strain gages does require a special fixture though, and the close proximity to the hot brake may cause a thermal drift that would require a temperature compensation method. The effectiveness curves using both the directly measured input torque values and the lookup table (calculated) torque values are given in Figures 4.19 through 4.22 for the four lining materials tested.

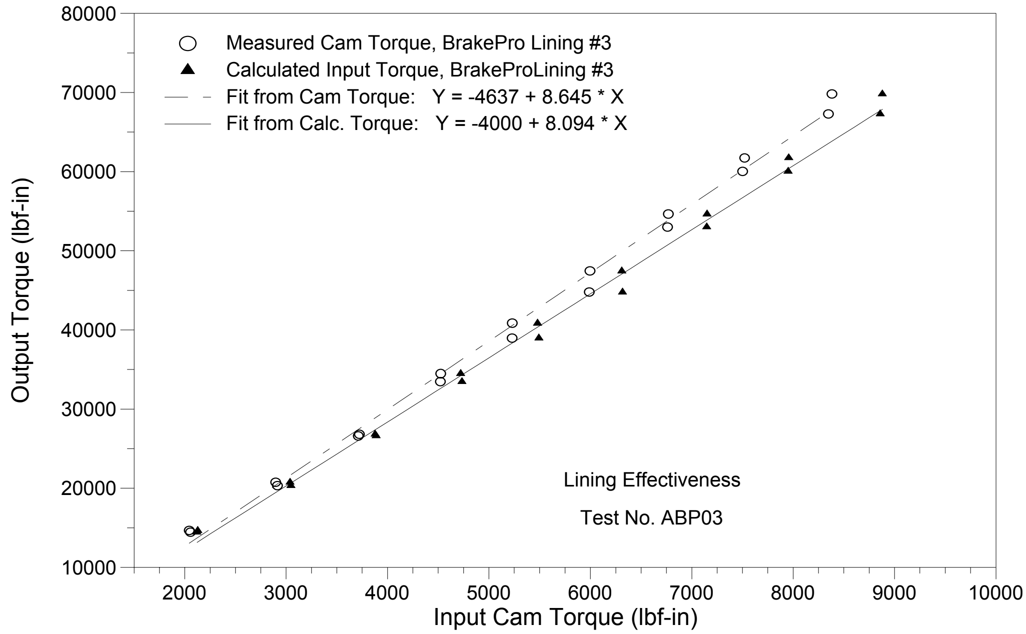


FIGURE 4.19 - Comparison of Measured and Calculated Input Torque – BrakePro 03

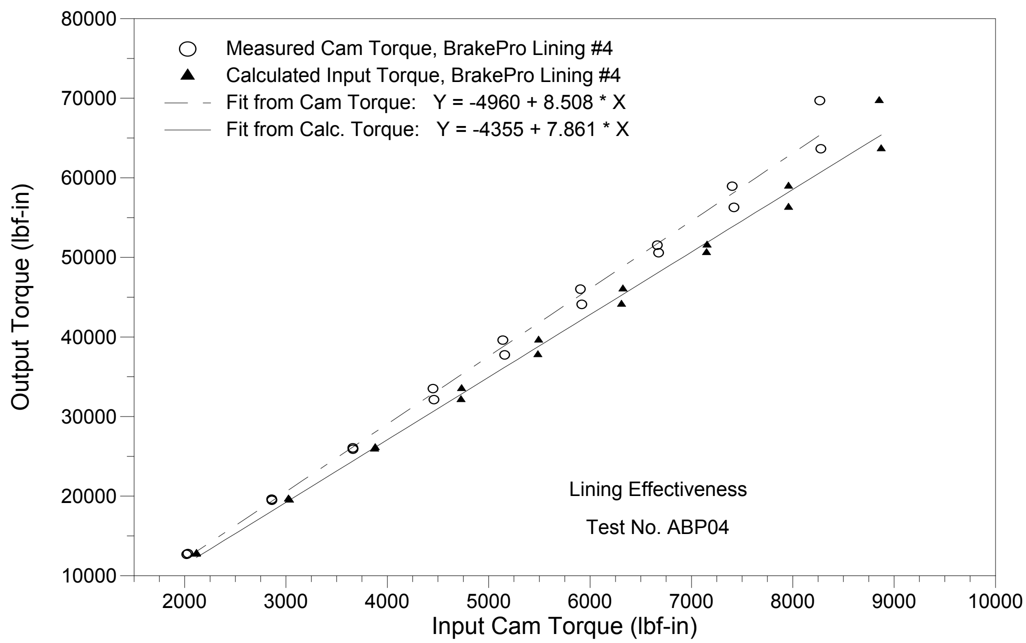


FIGURE 4.20 - Comparison of Measured and Calculated Input Torque – BrakePro 04

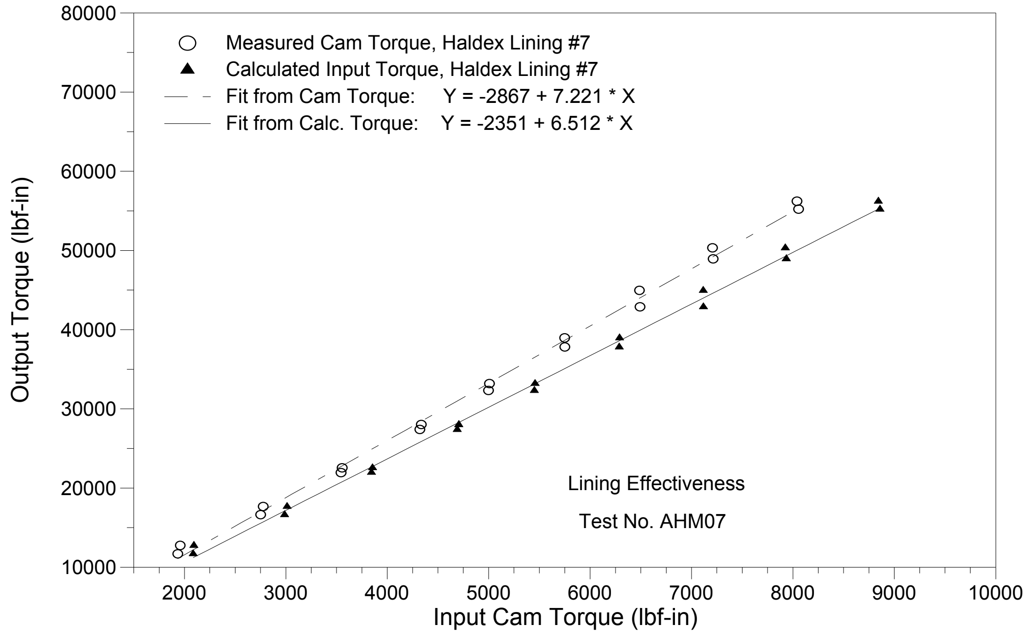


FIGURE 4.21 - Comparison of Measured and Calculated Input Torque – Haldex 07

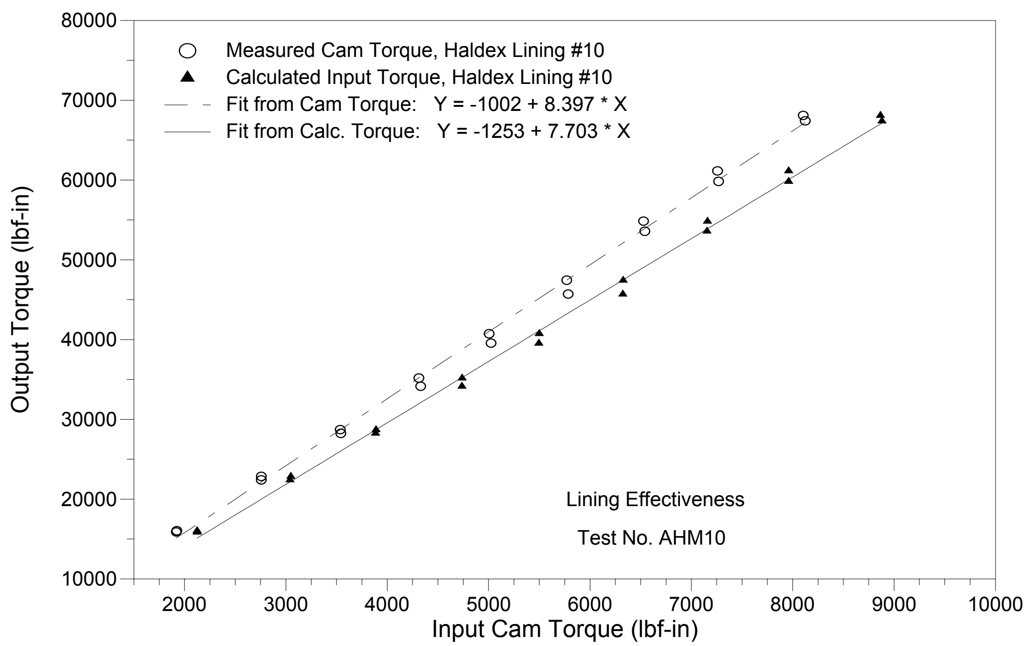


FIGURE 4.22 - Comparison of Measured and Calculated Input Torque – Haldex 10

For all four of the linings, the directly measured input torque is consistently lower than the calculated input torque. As the torque values increase, the two values diverge linearly. A linear regression was performed for the 72 pairs of measured and calculated input torques (4 linings x 18 effectiveness tests/lining). The r^2 value was 0.998 with the calculated input torque being 1.085 times the measured input torque. This very high r^2 value suggests that the two measurement methods produce results that differ by a multiplicative factor. This suggests that there was probably a calibration error for either the Abex cam torque or for the chamber lookup table. The Abex cam calibration shunt value was supplied by Abex, but the strain gage sensitivity could not be verified at VRTC.

5.0 SUMMARY & CONCLUSIONS

In 1986, development of a new SAE procedure, which was to be a more realistic measure of the performance of a lining material for a heavy vehicle brake, was initiated. This procedure has since been finalized and is SAE Recommended Practice J1802, ABrake Block Effectiveness Rating.@

Two round-robin studies evaluating SAE J1802 have been conducted in the past. The first study involved a single test fixture and one set of brake linings which were passed to nine test sites. The amount of variability in this study was relatively low with measured lining effectiveness values ranging from 7.1 to 8.0. The second involved seven test sites that used their own test fixtures. Three lining materials were tested in this second study. The level of variability in measured effectiveness values for this study was much greater (see Figure 1.2). Additional tests have been conducted in the past in an attempt to determine the cause of the differences among the test sites, but they failed to resolve the lab-to-lab differences.

The goal of this study was to further examine the test variability present in the SAE J1802 Test Procedure. In particular, four test fixtures were brought to VRTC to examine dimensional tolerance differences. Two of these fixtures were then selected to be used to perform SAE J1802 tests on several brake lining materials to see how much variability there was in the measured brake effectiveness values. A single operator performed the tests on a single dynamometer to reduce the number of potential sources of variability.

For the current study, the four test fixtures that were evaluated were from VRTC, Abex, Carlisle, and Haldex. Cam profile measurements and brake spider dimensional measurements were made on all four fixtures. All of the cam profiles and brake spider dimensional measurements were similar for all four of the fixtures evaluated. The small differences seen probably do not provide an explanation for why brake effectiveness measured values may be different for the various fixtures.

Two brake linings were evaluated: BrakePro and Haldex. Four linings from each manufacturer were conditioned by performing a complete J1802 test procedure using the VRTC test fixture . The brake lining and brake drums were measured pre- and post-conditioning and for those that were further evaluated, pre- and post-test. The BrakePro linings and the associated drums tended to wear slightly more than the Haldex linings.

From the four linings conditioned for each manufacturer, two were randomly and blindly (not knowing the effectiveness values calculated from the conditioning procedure) selected to be used in the evaluation of the Abex and Carlisle test fixtures. The two BrakePro linings selected happened to have very similar effectiveness values for the conditioning tests, while the Haldex linings were relatively different. The Abex and Carlisle fixtures were selected for evaluation because they were the two with the most complete set of parts sent to VRTC. The evaluation consisted of testing each lining selected using the J1802 normal temperature effectiveness test procedures on both test fixtures.

Comparing effectiveness values found using the two fixtures for each individual lining, i.e. one of the BrakePro linings on both the Abex and Carlisle fixtures, produced differences ranging from 1.3 to 10.2 percent. This amount of variation was similar to that found in the first round-robin study discussed above and was much less than that found in the second round-robin study. These results suggest that the variability found in the second round-robin came from sources other than the test fixtures. These sources may include, but not be limited to dynamometer differences, operator influences, setup procedure differences, and/or actual differences in the brake lining and/or drum materials. It should be noted that this was a very limited study and further testing would be required to make more definitive statements.

Comparing the effectiveness values found for the two linings from each manufacturer on each fixture, i.e, the two BrakePro linings on the Abex fixture, produced differences ranging from 2.5 to 16.9 percent. The two BrakePro linings evaluated had much less variability than the two Abex linings which was consistent with what was found during the conditioning procedure for the particular linings selected. When examining all four linings conditioned for each manufacturer, the BrakePro linings had slightly greater variability.

For this limited study, the amount of variability for any single combination of brake lining material/drum material tested across two different test fixtures was as high as 10.2 percent (Haldex 07 on the Abex and Carlisle test fixtures). The variability for multiple samples of brake lining material/drum material from the same manufacturer tested on a single test fixture was as high as 16.9 percent (Haldex 07 and Haldex 10 on the Abex fixture). These results suggest that even under the best test conditions (one test site, one dynamometer, one dynamometer operator, one test fixture) that the amount of variability in different brake lining material/drum material from the same manufacturer(s) and the same batch can be relatively high. When other potential sources of variability are considered (different test fixtures, different dynamometers, different dynamometer operators, etc.) the potential amount of variability may be greater than what would be acceptable for development of a Federal Motor Vehicle Safety Standard to rate brake linings.

The normal temperature effectiveness values from the VRTC conditioning runs were also compared to those found for the evaluation of the Abex and Carlisle fixture. The differences between the VRTC and Abex test fixtures ranged from 6.5 to 11.0 percent while those for the VRTC and Carlisle test fixtures ranged from 6.5 to 19.8 percent. These percentages are higher than those found for the differences between the Abex and Carlisle fixtures (1.3 to 10.2 percent). This is not surprising given that the lining materials had been subjected to the high temperature burnish and effectiveness test series between normal temperature effectiveness tests conducted on the VRTC fixture and those conducted on the Abex and Carlisle fixtures. These results suggest that a longer or higher temperature burnish may be required for the lining/drum to reach a stable condition prior to effectiveness testing being conducted.

The Abex test fixture had strain gages applied to the cam in a pattern that was designed to measure the input torque directly. It was found that this method of measurement appears to be appropriate and produces similar results to those found using the current method of creating a lookup table of force versus stroke for the service chamber. The differences between the two methods may be due to calibration errors.

In conclusion, the test matrix was designed to reduce the variability in test results due to dynamometer, operator, and set-up procedures differences and other unforeseen potential sources. Having a single operator perform testing with a single dynamometer using two different test fixtures produced results that had far less variability than those found in the second round-robin series discussed previously. While only a very limited number of tests were performed, the results suggest that much of the variability found in the second round-robin may have come from sources other than the test fixtures (dynamometer, operator, slightly different set-up procedures, brake lining and/or brake drum material differences, etc.).

Demonstrating that the variability seen during the second round-robin was due to sources other than the test fixtures would be extremely difficult. For example, to study the effects of having different dynamometer operators at the different sites (and, therefore, slightly different setup and operational procedures), a third round-robin could be performed. This round-robin would differ from the previous one in that, at each test site, testing would be performed twice, once with the sites regular operator and a second time with a common operator who would travel to all of the sites. The difficulties inherent in performing such testing are obvious. Similarly, test protocols could be developed to examine other possible sources of variability. A very large research program would be required to examine all of the possibilities.

6.0 REFERENCES

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APPENDIX A
Brake Spider Measurements

The Haldex, VRTC, and Carlisle brake spider measurements are given in Tables A.1 through A.6. Both Aas measured@ and Azeroed@ values are given for each brake spider. The method for zeroing the data is described in Section 3.3.2. The Abex measurements are also given in Section 3.3.2 (Tables 3.3 and 3.4). The method for collecting these measurements is fully explained in Section 3.2.2.

TABLE A.1 B Haldex Brake Spider Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7530	0.0000	-0.0001
S-Cam Shaft - F	1.5027	5.9971	0.0011
S-Cam Shaft - R	1.5013	5.9975	-0.0005
Anchor Pin Bore - A - F	1.2499	-6.7524	1.2534
Anchor Pin Bore - A - R	1.2501	-6.7534	1.2526
Anchor Pin Bore - B - F	1.2500	-6.7523	-1.2460
Anchor Pin Bore - B - R	1.2499	-6.7531	-1.2469
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6561	4.1220	-0.0180
2	0.6583	4.1185	22.5220
3	0.6600	4.1205	45.0740
4	0.6602	4.1223	67.6210
5	0.6591	4.1222	90.0970
6	0.6583	4.1270	112.5730
7	0.6572	4.1271	135.0920
8	0.6567	4.1300	157.4920
9	0.6560	4.1309	-180.0000
10	0.6558	4.1253	-157.5430
11	0.6594	4.1277	-135.0910
12	0.6557	4.1250	-112.5760
13	0.6573	4.1209	-90.0740
14	0.6607	4.1164	-67.6110
15	0.6578	4.1210	-45.0460
16	0.6574	4.1179	-22.5460
1 - Repeat	0.6565	4.1224	-0.0140

TABLE A.2 B Haldex Brake Spider Zeroed Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7530	0.0000	0.0000
S-Cam Shaft - F	1.5027	5.9971	0.0012
S-Cam Shaft - R	1.5013	5.9975	-0.0004
Anchor Pin Bore - A - F	1.2499	-6.7524	1.2535
Anchor Pin Bore - A - R	1.2501	-6.7534	1.2527
Anchor Pin Bore - B - F	1.2500	-6.7523	-1.2459
Anchor Pin Bore - B - R	1.2499	-6.7531	-1.2468
Pilot Bolt No.	Dia. (inch)	Radius (inch)	Angle (deg)
1	0.6561	4.1220	0.0000
2	0.6583	4.1185	22.5400
3	0.66 00	4.1205	45.0920
4	0.6602	4.1223	67.6390
5	0.6591	4.1222	90.1150
6	0.6583	4.1270	112.5910
7	0.6572	4.1271	135.1100
8	0.6567	4.1300	157.5100
9	0.6560	4.1309	-179.9820
10	0.6558	4.1253	-157.5250
11	0.6594	4.1277	-135.0730
12	0.6557	4.1250	-112.5580
13	0.6573	4.1209	-90.0560
14	0.6607	4.1164	-67.5930
15	0.6578	4.1210	-45.0280
16	0.6574	4.1179	-22.5280
1 - Repeat	0.6565	4.1224	0.0040

TABLE A.3 B VRTC Brake Spider Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7531	0.0001	0.0001
S-Cam Shaft - F	1.5032	5.9928	-0.0003
S-Cam Shaft - R	1.5036	5.9941	0.0001
Anchor Pin Bore - A - F	1.2528	-6.7617	1.2492
Anchor Pin Bore - A - R	1.2510	-6.7609	1.2488
Anchor Pin Bore - B - F	1.2523	-6.7573	-1.2482
Anchor Pin Bore - B - R	1.2515	-6.7561	-1.2498
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6563	4.1269	0.0090
2	0.6576	4.1238	22.5060
3	0.6583	4.1248	45.0120
4	0.6598	4.1251	67.5780
5	0.6588	4.1216	90.0070
6	0.6583	4.1243	112.5360
7	0.6562	4.1235	135.0650
8	0.6593	4.1252	157.4840
9	0.6559	4.1276	-179.9910
10	0.6564	4.1218	-157.4970
11	0.6575	4.1251	-135.0430
12	0.6583	4.1237	-112.5250
13	0.6572	4.1207	-90.0000
14	0.6614	4.1192	-67.5100
15	0.6583	4.1235	-44.9960
16	0.6580	4.1227	-22.4930
1 - Repeat	0.6563	4.1272	-0.0130

TABLE A.4 B VRTC Brake Spider Zeroed Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7531	0.0000	0.0000
S-Cam Shaft - F	1.5032	5.9927	-0.0004
S-Cam Shaft - R	1.5036	5.9940	0.0000
Anchor Pin Bore - A - F	1.2528	-6.7618	1.2491
Anchor Pin Bore - A - R	1.2510	-6.7610	1.2487
Anchor Pin Bore - B - F	1.2523	-6.7574	-1.2483
Anchor Pin Bore - B - R	1.2515	-6.7562	-1.2499
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6563	4.1269	0.0000
2	0.6576	4.1238	22.4970
3	0.6583	4.1248	45.0030
4	0.6598	4.1251	67.5690
5	0.6588	4.1216	89.9980
6	0.6583	4.1243	112.5270
7	0.6562	4.1235	135.0560
8	0.6593	4.1252	157.4750
9	0.6559	4.1276	-180.0000
10	0.6564	4.1218	-157.5060
11	0.6575	4.1251	-135.0520
12	0.6583	4.1237	-112.5340
13	0.6572	4.1207	-90.0090
14	0.6614	4.1192	-67.5190
15	0.6583	4.1235	-45.0050
16	0.6580	4.1227	-22.5020
1 - Repeat	0.6563	4.1272	-0.0220

TABLE A.5 ʙ Carlisle Spider Measurement Values

	Dia. (inch)	Location: X (inch)	Location: Y (inch)
Pilot Bore	6.7540	-0.0001	0.0000
S-Cam Shaft - F	1.5033	5.9964	0.0008
S-Cam Shaft - R	1.5003	5.9970	-0.0018
Anchor Pin Bore - A - F	1.2497	-6.7547	1.2540
Anchor Pin Bore - A - R	1.2496	-6.7551	1.2544
Anchor Pin Bore - B - F	1.2496	-6.7545	-1.2442
Anchor Pin Bore - B - R	1.2495	-6.7546	-1.2456
Pilot Bolt No.	**Dia. (inch)**	**Radius (inch)**	**Angle (deg)**
1	0.6562	4.1206	-0.0840
2	0.6584	4.1183	22.4750
3	0.6589	4.1202	44.9800
4	0.6594	4.1223	67.5910
5	0.6591	4.1213	90.0470
6	0.6578	4.1271	112.5300
7	0.6571	4.1274	135.0390
8	0.6582	4.1308	157.4380
9	0.6559	4.1331	179.9500
10	0.6565	4.1264	-157.5970
11	0.6596	4.1283	-135.1620
12	0.6587	4.1263	-112.6690
13	0.6575	4.1234	-90.1500
14	0.6618	4.1171	-67.6720
15	0.6585	4.1208	-45.1300
16	0.6573	4.1177	-22.6040
1 - Repeat	0.6568	4.1211	-0.0890

TABLE A.6 B Carlisle Brake Spider Zeroed Measurement Values

		Location:	
	Dia. (inch)	X (inch)	Y (inch)
Pilot Bore	6.7574	0.0000	0.0000
S-Cam Shaft - F	1.5033	5.9965	0.0008
S-Cam Shaft - R	1.5003	5.9971	-0.0018
Anchor Pin Bore - A - F	1.2497	-6.7546	1.2540
Anchor Pin Bore - A - R	1.2496	-6.7550	1.2544
Anchor Pin Bore - B - F	1.2496	-6.7544	-1.2442
Anchor Pin Bore - B - R	1.2495	-6.7545	-1.2456
Pilot Bolt No.	Dia. (inch)	Radius (inch)	Angle (deg)
1	0.6562	4.1206	0.0000
2	0.6584	4.1183	22.5590
3	0.6589	4.1202	45.0640
4	0.6594	4.1223	67.6750
5	0.6591	4.1213	90.1310
6	0.6578	4.1271	112.6140
7	0.6571	4.1274	135.1230
8	0.6582	4.1308	157.5220
9	0.6559	4.1331	-179.9660
10	0.6565	4.1264	-157.5130
11	0.6596	4.1283	-135.0780
12	0.6587	4.1263	-112.5850
13	0.6575	4.1234	-90.0660
14	0.6618	4.1171	-67.5880
15	0.6585	4.1208	-45.0460
16	0.6573	4.1177	-22.5200
1 - Repeat	0.6568	4.1211	-0.0050

APPENDIX B
Brake Lining and Drum Measurements

The pre- and post-test lining thickness measurement values are given in Table B.1. The method for measuring the brake lining thickness values is given in Section 4.3.3. Initial and final measurement values are given for each time a lining material had either a burnish procedure or a test procedure performed on it. The difference between initial and final values and the final value as a percentage of the original value are also given.

The brake shoe and drum weight measurements are given in Table B.2. Initial and final measurements are listed. The difference between initial and final weight and the final weight as a percentage of initial weight are also listed.

The leading and trailing shoe brake arch measurements are given in Tables B.3 and B.4 respectively. Pre- and post-test measurements are given. The difference in the pre- and post-test values, the mean and standard deviation for each lining, and the mean and standard deviation for each measurement position are given.

TABLE B.1: Pre- and Post Test Lining Thickness Measurements (inches)

Fixture		Position No.:	1	2	3	4	5	6	7	8	9	10	11	12	Avg for 1-12
VRTC															
	Initial	**Test No: 98-1**	0.907	0.889	0.965	0.958	1.004	1.018	0.973	0.997	0.870	0.881	0.779	0.772	
Lead	Final	**Test Set: set01**	0.912	0.885	0.957	0.943	0.983	1.002	0.976	0.980	0.846	0.864	0.762	0.763	
		Δ(init-fin)	-0.005	0.004	0.008	0.015	0.021	0.016	-0.003	0.017	0.024	0.017	0.017	0.009	
		% init.	100.55%	99.55%	99.17%	98.43%	97.91%	98.43%	100.31%	98.29%	97.24%	98.07%	97.82%	98.83%	98.72%
	Initial	**Test No: 98-1**	0.887	0.903	0.936	0.964	0.953	0.999	0.932	0.972	0.839	0.856	0.753	0.741	
Trail	Final	**Test Set: set01**	0.874	0.896	0.927	0.956	0.950	0.991	0.928	0.967	0.834	0.856	0.750	0.745	
		Δ(init-fin)	0.013	0.007	0.009	0.008	0.003	0.008	0.004	0.005	0.005	0.000	0.003	-0.004	
		% init.	98.53%	99.22%	99.04%	99.17%	99.69%	99.20%	99.57%	99.49%	99.40%	100.00%	99.60%	100.54%	99.45%
VRTC															
	Initial	**Test No: 98-2**	0.869	0.878	0.926	0.938	0.964	0.997	0.943	0.966	0.854	0.855	0.766	0.75	
Lead	Final	**Test Set: set02**	0.873	0.874	0.921	0.928	0.950	0.980	0.928	0.958	0.844	0.848	0.763	0.748	
		Δ(init-fin)	-0.004	0.004	0.005	0.010	0.014	0.017	0.015	0.008	0.010	0.007	0.003	0.002	
		% init.	100.46%	99.54%	99.46%	98.93%	98.55%	98.29%	98.41%	99.17%	98.83%	99.18%	99.61%	99.73%	99.18%
	Initial	**Test No: 98-2**	0.908	0.894	0.950	0.949	0.965	0.994	0.921	0.965	0.812	0.845	0.725	0.744	
Trail	Final	**Test Set: set01**	0.882	0.857	0.938	0.912	0.960	0.966	0.920	0.952	0.813	0.847	0.726	0.743	
		Δ(init-fin)	0.026	0.037	0.012	0.037	0.005	0.028	0.001	0.013	-0.001	-0.002	-0.001	0.001	
		% init.	97.14%	95.86%	98.74%	96.10%	99.48%	97.18%	99.89%	98.65%	100.12%	100.24%	100.14%	99.87%	98.62%
VRTC															
	Initial	**Test No: 98-3**	0.898	0.906	0.936	0.959	0.951	0.976	0.918	0.945	0.819	0.826	0.734	0.720	
Lead	Final	**Test Set: set03**	0.903	0.903	0.938	0.953	0.944	0.969	0.908	0.938	0.806	0.817	0.726	0.713	
		Δ(init-fin)	-0.005	0.003	-0.002	0.006	0.007	0.007	0.010	0.007	0.013	0.009	0.008	0.007	
		% init.	100.56%	99.67%	100.21%	99.37%	99.26%	99.28%	98.91%	99.26%	98.41%	98.91%	98.91%	99.03%	99.32%
	Initial	**Test No: 98-3**	0.902	0.927	0.954	0.994	0.974	1.017	0.973	0.983	0.849	0.849	0.756	0.738	
Trail	Final	**Test Set: set03**	0.879	0.910	0.939	0.982	0.966	1.011	0.945	0.981	0.845	0.855	0.755	0.740	
		Δ(init-fin)	0.023	0.017	0.015	0.012	0.008	0.006	0.028	0.002	0.004	-0.006	0.001	-0.002	
		% init.	97.45%	98.17%	98.43%	98.79%	99.18%	99.41%	97.12%	99.80%	99.53%	100.71%	99.87%	100.27%	99.06%
VRTC															
	Initial	**Test No: 98-4**	0.891	0.903	0.932	0.964	0.943	0.985	0.912	0.956	0.815	0.817	0.734	0.729	
Lead	Final	**Test Set: set04**	0.895	0.895	0.932	0.952	0.935	0.974	0.902	0.947	0.806	0.809	0.730	0.725	
		Δ(init-fin)	-0.004	0.008	0.000	0.012	0.008	0.011	0.010	0.009	0.009	0.008	0.004	0.004	
		% init.	100.45%	99.11%	100.00%	98.76%	99.15%	98.88%	98.90%	99.06%	98.90%	99.02%	99.46%	99.45%	99.26%
	Initial	**Test No: 98-4**	0.869	0.900	0.951	0.960	0.980	1.007	0.952	0.979	0.854	0.856	0.764	0.760	
Trail	Final	**Test Set: set04**	0.861	0.888	0.928	0.945	0.969	0.998	0.950	0.975	0.855	0.861	0.770	0.760	
		Δ(init-fin)	0.008	0.012	0.023	0.015	0.011	0.009	0.002	0.004	-0.001	-0.005	-0.006	0.000	
		% init.	99.08%	98.67%	97.58%	98.44%	98.88%	99.11%	99.79%	99.59%	100.12%	100.58%	100.79%	100.00%	99.38%

TABLE B.1: Pre- and Post Test Lining Thickness Measurements (inches) (Continued)

Fixture		Position No.:	1	2	3	4	5	6	7	8	9	10	11	12	Avg for 1-12
VRTC															
	Initial	**Test No: 98-5**	0.886	0.910	0.931	0.964	0.953	0.986	0.930	0.957	0.835	0.836	0.757	0.730	
Lead	Final	**Test Set: set05**	0.894	0.905	0.930	0.959	0.948	0.985	0.925	0.957	0.829	0.834	0.752	0.726	
		Δ(init-fin)	-0.008	0.005	0.001	0.005	0.005	0.001	0.005	0.000	0.006	0.002	0.005	0.004	
		% init.	100.90%	99.45%	99.89%	99.48%	99.48%	99.90%	99.46%	100.00%	99.28%	99.76%	99.34%	99.45%	99.70%
	Initial	**Test No: 98-5**	0.926	0.944	0.965	0.994	0.972	1.006	0.932	0.965	0.822	0.828	0.737	0.715	
Trail	Final	**Test Set: set05**	0.903	0.931	0.959	0.988	0.973	1.005	0.934	0.966	0.823	0.830	0.735	0.720	
		Δ(init-fin)	0.023	0.013	0.006	0.006	-0.001	0.001	-0.002	-0.001	-0.001	-0.002	0.002	-0.005	
		% init.	97.52%	98.62%	99.38%	99.40%	100.10%	99.90%	100.21%	100.10%	100.12%	100.24%	99.73%	100.70%	99.67%
VRTC															
	Initial	**Test No: 98-6**	0.905	0.904	0.936	0.961	0.948	0.993	0.914	0.952	0.816	0.822	0.736	0.721	
Lead	Final	**Test Set: set08**	0.914	0.914	0.938	0.960	0.947	0.993	0.910	0.951	0.810	0.819	0.736	0.718	
		Δ(init-fin)	-0.009	-0.010	-0.002	0.001	0.001	0.000	0.004	0.001	0.006	0.003	0.000	0.003	
		% init.	100.99%	101.11%	100.21%	99.90%	99.89%	100.00%	99.56%	99.89%	99.26%	99.64%	100.00%	99.58%	100.00%
	Initial	**Test No: 98-6**	0.929	0.950	0.958	0.984	0.969	1.030	0.935	0.990	0.823	0.853	0.735	0.758	
Trail	Final	**Test Set: set08**	0.908	0.940	0.950	0.978	0.970	1.031	0.938	0.993	0.825	0.857	0.739	0.762	
		Δ(init-fin)	0.021	0.010	0.008	0.006	-0.001	-0.001	-0.003	-0.003	-0.002	-0.004	-0.004	-0.004	
		% init.	97.74%	98.95%	99.16%	99.39%	100.10%	100.10%	100.32%	100.30%	100.24%	100.47%	100.54%	100.53%	99.82%
VRTC															
	Initial	**Test No: 98-7**	0.884	0.892	0.929	0.941	0.961	0.987	0.935	0.958	0.840	0.838	0.756	0.730	
Lead	Final	**Test Set: set09**	0.889	0.890	0.932	0.939	0.960	0.987	0.933	0.958	0.837	0.835	0.756	0.732	
		Δ(init-fin)	-0.005	0.002	-0.003	0.002	0.001	0.000	0.002	0.000	0.003	0.003	0.000	-0.002	
		% init.	100.57%	99.78%	100.32%	99.79%	99.90%	100.00%	99.79%	100.00%	99.64%	99.64%	100.00%	100.27%	99.97%
	Initial	**Test No: 98-7**	0.896	0.903	0.960	0.957	0.990	1.022	0.955	1.001	0.854	0.881	0.758	0.775	
Trail	Final	**Test Set: set09**	0.878	0.893	0.959	0.949	0.994	1.021	0.957	1.002	0.855	0.885	0.761	0.782	
		Δ(init-fin)	0.018	0.010	0.001	0.008	-0.004	0.001	-0.002	-0.001	-0.001	-0.004	-0.003	-0.007	
		% init.	97.99%	98.89%	99.90%	99.16%	100.40%	99.90%	100.21%	100.10%	100.12%	100.45%	100.40%	100.90%	99.87%
VRTC															
	Initial	**Test No: 98-8**	0.922	0.927	0.963	0.977	0.991	1.025	0.957	0.994	0.835	0.861	0.762	0.756	
Lead	Final	**Test Set: set10**	0.930	0.922	0.965	0.972	0.985	1.022	0.950	0.990	0.826	0.853	0.755	0.750	
		Δ(init-fin)	-0.008	0.005	-0.002	0.005	0.006	0.003	0.007	0.004	0.009	0.008	0.007	0.006	
		% init.	100.87%	99.46%	100.21%	99.49%	99.39%	99.71%	99.27%	99.60%	98.92%	99.07%	99.08%	99.21%	99.52%
	Initial	**Test No: 98-8**	0.917	0.929	0.939	0.968	0.941	0.993	0.906	0.950	0.786	0.807	0.701	0.714	
Trail	Final	**Test Set: set10**	0.909	0.925	0.936	0.966	0.944	0.994	0.899	0.956	0.778	0.808	0.697	0.716	
		Δ(init-fin)	0.008	0.004	0.003	0.002	-0.003	-0.001	0.007	-0.006	0.008	-0.001	0.004	-0.002	
		% init.	99.13%	99.57%	99.68%	99.79%	100.32%	100.10%	99.23%	100.63%	98.98%	100.12%	99.43%	100.28%	99.77%

TABLE B.1: Pre- and Post Test Lining Thickness Measurements (inches) (Continued)

Fixture		Position No.:	1	2	3	4	5	6	7	8	9	10	11	12	Avg for 1-12
CARLISLE		**Test No: 98-9**													
		Test Set: set02							**aborted run**						
CARLISLE															
	Initial	**Test No: 98-10**	0.894	0.905	0.930	0.959	0.948	0.985	0.925	0.957	0.829	0.834	0.752	0.726	
Lead	Final	**Test Set: set07**	0.894	0.903	0.929	0.957	0.946	0.984	0.922	0.955	0.825	0.832	0.748	0.728	
		Δ(init-fin)	0.000	0.002	0.001	0.002	0.002	0.001	0.003	0.002	0.004	0.002	0.004	-0.002	
		% init.	100.00%	99.78%	99.89%	99.79%	99.79%	99.90%	99.68%	99.79%	99.52%	99.76%	99.47%	100.28%	99.80%
	Initial	**Test No: 98-10**	0.903	0.931	0.959	0.988	0.973	1.005	0.934	0.966	0.823	0.830	0.735	0.720	
Trail	Final	**Test Set: set07**	0.901	0.929	0.956	0.985	0.972	1.004	0.933	0.966	0.821	0.830	0.735	0.720	
		Δ(init-fin)	0.002	0.002	0.003	0.003	0.001	0.001	0.001	0.000	0.002	0.000	0.000	0.000	
		% init.	99.78%	99.79%	99.69%	99.70%	99.90%	99.90%	99.89%	100.00%	99.76%	100.00%	100.00%	100.00%	99.87%
CARLISLE															
	Initial	**Test No: 98-11**	0.930	0.922	0.965	0.972	0.985	1.022	0.950	0.990	0.826	0.853	0.755	0.750	
Lead	Final	**Test Set: set10**	0.929	0.922	0.962	0.970	0.981	1.023	0.945	0.988	0.822	0.851	0.751	0.748	
		Δ(init-fin)	0.001	0.000	0.003	0.002	0.004	-0.001	0.005	0.002	0.004	0.002	0.004	0.002	
		% init.	99.89%	100.00%	99.69%	99.79%	99.59%	100.10%	99.47%	99.80%	99.52%	99.77%	99.47%	99.73%	99.74%
	Initial	**Test No: 98-11**	0.909	0.925	0.936	0.966	0.944	0.994	0.899	0.956	0.778	0.808	0.697	0.716	
Trail	Final	**Test Set: set10**	0.901	0.924	0.935	0.963	0.944	0.992	0.900	0.954	0.777	0.807	0.696	0.716	
		Δ(init-fin)	0.008	0.001	0.001	0.003	0.000	0.002	-0.001	0.002	0.001	0.001	0.001	0.000	
		% init.	99.12%	99.89%	99.89%	99.69%	100.00%	99.80%	100.11%	99.79%	99.87%	99.88%	99.86%	100.00%	99.82%
CARLISLE															
	Initial	**Test No: 98-12**	0.895	0.895	0.932	0.952	0.935	0.974	0.902	0.947	0.806	0.809	0.730	0.725	
Lead	Final	**Test Set: set04**	0.896	0.891	0.929	0.948	0.932	0.970	0.898	0.943	0.803	0.806	0.727	0.721	
		Δ(init-fin)	-0.001	0.004	0.003	0.004	0.003	0.004	0.004	0.004	0.003	0.003	0.003	0.004	
		% init.	100.11%	99.55%	99.68%	99.58%	99.68%	99.59%	99.56%	99.58%	99.63%	99.63%	99.59%	99.45%	99.63%
	Initial	**Test No: 98-12**	0.861	0.888	0.928	0.945	0.969	0.998	0.950	0.975	0.855	0.861	0.770	0.760	
Trail	Final	**Test Set: set04**	0.857	0.880	0.923	0.945	0.965	0.993	0.947	0.973	0.854	0.859	0.770	0.759	
		Δ(init-fin)	0.004	0.008	0.005	0.000	0.004	0.005	0.003	0.002	0.001	0.002	0.000	0.001	
		% init.	99.54%	99.10%	99.46%	100.00%	99.59%	99.50%	99.68%	99.79%	99.88%	99.77%	100.00%	99.87%	99.68%
CARLISLE															
	Initial	**Test No: 98-13**	0.903	0.903	0.938	0.953	0.944	0.969	0.907	0.938	0.806	0.817	0.726	0.713	
Lead	Final	**Test Set: set03**	0.903	0.899	0.934	0.949	0.940	0.964	0.902	0.933	0.802	0.813	0.723	0.711	
		Δ(init-fin)	0.000	0.004	0.004	0.004	0.004	0.005	0.005	0.005	0.004	0.004	0.003	0.002	
		% init.	100.00%	99.56%	99.57%	99.58%	99.58%	99.48%	99.45%	99.47%	99.50%	99.51%	99.59%	99.72%	99.58%
	Initial	**Test No: 98-13**	0.879	0.910	0.939	0.982	0.966	1.011	0.945	0.981	0.845	0.855	0.755	0.740	
Trail	Final	**Test Set: set03**	0.875	0.906	0.933	0.976	0.962	1.006	0.942	0.978	0.843	0.853	0.754	0.740	
		Δ(init-fin)	0.004	0.004	0.006	0.006	0.004	0.005	0.003	0.003	0.002	0.002	0.001	0.000	
		% init.	99.54%	99.56%	99.36%	99.39%	99.59%	99.51%	99.68%	99.69%	99.76%	99.77%	99.87%	100.00%	99.64%

TABLE B.1: Pre- and Post Test Lining Thickness Measurements (inches) (Continued)

Fixture		Position No.:	1	2	3	4	5	6	7	8	9	10	11	12	Avg for 1-12
ABEX															
	Initial	**Test No: 98-14**	0.903	0.899	0.934	0.949	0.940	0.964	0.902	0.933	0.802	0.813	0.723	0.711	
Lead	Final	**Test Set: set03**	0.903	0.896	0.930	0.945	0.933	0.958	0.895	0.928	0.796	0.808	0.720	0.709	
		Δ(init-fin)	0.000	0.003	0.004	0.004	0.007	0.006	0.007	0.005	0.006	0.005	0.003	0.002	
		% init.	100.00%	99.67%	99.57%	99.58%	99.26%	99.38%	99.22%	99.46%	99.25%	99.38%	99.59%	99.72%	99.51%
	Initial	**Test No: 98-14**	0.875	0.906	0.933	0.976	0.962	1.006	0.942	0.978	0.843	0.853	0.754	0.740	
Trail	Final	**Test Set: set03**	0.871	0.902	0.928	0.970	0.956	1.000	0.937	0.973	0.840	0.851	0.752	0.739	
		Δ(init-fin)	0.004	0.004	0.005	0.006	0.006	0.006	0.005	0.005	0.003	0.002	0.002	0.001	
		% init.	99.54%	99.56%	99.46%	99.39%	99.38%	99.40%	99.47%	99.49%	99.64%	99.77%	99.73%	99.86%	99.56%
ABEX															
	Initial	**Test No: 98-15**	0.894	0.903	0.929	0.957	0.946	0.984	0.922	0.955	0.825	0.832	0.748	0.728	
Lead	Final	**Test Set: set07**	0.893	0.901	0.927	0.955	0.943	0.982	0.918	0.954	0.821	0.831	0.745	0.726	
		Δ(init-fin)	0.001	0.002	0.002	0.002	0.003	0.002	0.004	0.001	0.004	0.001	0.003	0.002	
		% init.	99.89%	99.78%	99.78%	99.79%	99.68%	99.80%	99.57%	99.90%	99.52%	99.88%	99.60%	99.73%	99.74%
	Initial	**Test No: 98-15**	0.901	0.929	0.956	0.985	0.972	1.004	0.933	0.966	0.821	0.830	0.735	0.720	
Trail	Final	**Test Set: set07**	0.898	0.926	0.952	0.982	0.970	1.002	0.932	0.965	0.820	0.830	0.735	0.720	
		Δ(init-fin)	0.003	0.003	0.004	0.003	0.002	0.002	0.001	0.001	0.001	0.000	0.000	0.000	
		% init.	99.67%	99.68%	99.58%	99.70%	99.79%	99.80%	99.89%	99.90%	99.88%	100.00%	100.00%	100.00%	99.82%
ABEX															
	Initial	**Test No: 98-16**	0.896	0.891	0.929	0.948	0.932	0.970	0.898	0.943	0.803	0.806	0.727	0.721	
Lead	Final	**Test Set: set04**	0.895	0.887	0.925	0.945	0.926	0.965	0.892	0.938	0.798	0.802	0.724	0.721	
		Δ(init-fin)	0.001	0.004	0.004	0.003	0.006	0.005	0.006	0.005	0.005	0.004	0.003	0.000	
		% init.	99.89%	99.55%	99.57%	99.68%	99.36%	99.48%	99.33%	99.47%	99.38%	99.50%	99.59%	100.00%	99.57%
	Initial	**Test No: 98-16**	0.857	0.880	0.923	0.945	0.965	0.993	0.947	0.973	0.854	0.859	0.770	0.759	
Trail	Final	**Test Set: set04**	0.852	0.880	0.918	0.938	0.960	0.988	0.944	0.968	0.852	0.856	0.769	0.757	
		Δ(init-fin)	0.005	0.000	0.005	0.007	0.005	0.005	0.003	0.005	0.002	0.003	0.001	0.002	
		% init.	99.42%	100.00%	99.46%	99.26%	99.48%	99.50%	99.68%	99.49%	99.77%	99.65%	99.87%	99.74%	99.61%
ABEX															
	Initial	**Test No: 98-17**	0.929	0.922	0.962	0.970	0.981	1.023	0.945	0.988	0.822	0.851	0.751	0.748	
Lead	Final	**Test Set: set10**	0.928	0.921	0.959	0.968	0.979	1.018	0.941	0.985	0.818	0.848	0.749	0.748	
		Δ(init-fin)	0.001	0.001	0.003	0.002	0.002	0.005	0.004	0.003	0.004	0.003	0.002	0.000	
		% init.	99.89%	99.89%	99.69%	99.79%	99.80%	99.51%	99.58%	99.70%	99.51%	99.65%	99.73%	100.00%	99.73%
	Initial	**Test No: 98-17**	0.904	0.924	0.935	0.963	0.944	0.992	0.900	0.954	0.777	0.807	0.696	0.716	
Trail	Final	**Test Set: set10**	0.904	0.923	0.933	0.961	0.942	0.990	0.899	0.953	0.777	0.807	0.696	0.716	
		Δ(init-fin)	0.000	0.001	0.002	0.002	0.002	0.002	0.001	0.001	0.000	0.000	0.000	0.000	
		% init.	100.00%	99.89%	99.79%	99.79%	99.79%	99.80%	99.89%	99.90%	100.00%	100.00%	100.00%	100.00%	99.90%

TABLE B.2 - Shoe Assembly and Drum Weights (pounds)

Fixture		Shoe Weight			Drum Weight	
			Lead	**Trail**		
VRTC	Test No: 98-1	Initial	25.7	25.4	Initial	110.2
	Test Set: set01	Final	25.5	25.3	Final	110.0
		♠(init-fin)	0.2	0.1	♠(init-fin)	0.2
		% Initial	99.22%	99.61%	% Initial	99.82%
	Test No: 98-2	Initial	25.5	24.7	Initial	110.7
	Test Set: set02	Final	25.3	24.6	Final	110.5
		♠(init-fin)	0.2	0.1	♠(init-fin)	0.2
		% Initial	99.22%	99.60%	% Initial	99.82%
	Test No: 98-3	Initial	24.6	25.0	Initial	107.9
	Test Set: set03	Final	24.4	24.8	Final	107.8
		♠(init-fin)	0.2	0.2	♠(init-fin)	0.1
		% Initial	99.19%	99.20%	% Initial	99.91%
	Test No: 98-4	Initial	24.9	25.4	Initial	110.2
	Test Set: set04	Final	24.7	25.2	Final	110.0
		♠(init-fin)	0.2	0.2	♠(init-fin)	0.2
		% Initl. Wgt	99.20%	99.21%	% Initl. Wgt	99.82%
	Test No: 98-5	Initial	24.7	25	Initial	110.2
	Test Set: set07	Final	24.7	24.9	Final	110.1
		♠(init-fin)	0.0	0.1	♠(init-fin)	0.1
		% Initial	100.00%	99.60%	% Initial	99.91%
	Test No: 98-6	Initial	24.7	25.2	Initial	110.4
	Test Set: set08	Final	24.7	25.1	Final	110.3
		♠(init-fin)	0.00	0.1	♠(init-fin)	0.1
		% Initial	100.00%	99.60%	% Initial	99.91%
	Test No: 98-7	Initial	25.3	25.7	Initial	110.2
	Test Set: set09	Final	N/A	25.6	Final	110.1
		♠(init-fin)		0.1	♠(init-fin)	0.1
		% Initial		99.61%	% Initial	99.91%
	Test No: 98-8	Initial	25.2	25.1	Initial	109.1
	Test Set: set10	Final	25.1	25.0	Final	109.0
		♠(init-fin)	0.1	0.1	♠(init-fin)	0.1
		% Initial	99.60%	99.60%	% Initial	99.91%

TABLE B.2 B Shoe Assembly and Drum Weights (pounds)(Continued)

Fixture		Shoe Weight			Drum Weight	
			Lead	**Trail**		
CARLISLE	Test No: 98-9	aborted run				
	Test Set: set02					
	Test No: 98-10	Initial	24.7	24.9	Initial	110.1
	Test Set: set07	Final	24.6	24.9	Final	110.1
		□(init-fin)	0.1	0.0	□(init-fin)	0.0
		% Initial	99.60%	100.00%	% Initial	100.00%
	Test No: 98-11	Initial	25.1	25.1	Initial	109.0
	Test Set: set10	Final	25.0	25.0	Final	109.0
		□(init-fin)	0.1	0.1	□(init-fin)	0.0
		% Initial	99.60%	99.60%	% Initial	100.00%
	Test No: 98-12	Initial	24.7	25.2	Initial	110.0
	Test Set: set04	Final	24.7	25.1	Final	110.0
		□(init-fin)	0.0	0.1	□(init-fin)	0.0
		% Initial	100.00%	99.60%	% Initial	100.00%
	Test No: 98-13	Initial	24.4	24.8	Initial	107.8
	Test Set: set03	Final	24.4	24.8	Final	107.8
		□(init-fin)	0.0	0.0	□(init-fin)	0.0
		% Initial	100.00%	100.00%	% Initial	100.00%
ABEX	Test No: 98-14	Initial	24.4	24.8	Initial	107.8
	Test Set: set03	Final	24.3	24.7	Final	107.8
		□(init-fin)	0.1	0.1	□(init-fin)	0.0
		% Initial	99.59%	99.60%	% Initial	100.00%
	Test No: 98-15	Initial	24.6	24.9	Initial	110.1
	Test Set: set07	Final	24.5	24.8	Final	110.1
		□(init-fin)	0.1	0.1	□(init-fin)	0.0
		% Initial	99.59%	1.00	% Initial	100.00%
	Test No: 98-16	Initial	24.7	25.1	Initial	110.1
	Test Set: set04	Final	24.6	25.0	Final	110.0
		□(init-fin)	0.1	0.1	□(init-fin)	0.0
		% Initial	99.60%	99.60%	% Initial	100.00%
	Test No: 98-17	Initial	25.0	25.0	Initial	109.0
	Test Set: set10	Final	24.9	24.9	Final	108.9
		□(init-fin)	0.1	0.1	□(init-fin)	0.1
		% Initial	99.60%	99.60%	% Initial	99.91%

TABLE B.3 B Radius Measurements - Leading Brake (inches)

Lining Position	Set 01	Set 02	Set 03	Set 04	Set 07	Set 08	Set 09	Set 10	Mean	Std. Dev.
1 Initial	8.184	8.163	8.153	8.153	8.159	8.163	8.164	8.180	8.165	0.011
Final		8.139	8.161	8.162	8.168	8.177	8.176	8.200	8.169	0.017
Difference		0.024	-0.008	-0.009	-0.009	-0.014	-0.012	-0.020	-0.004	
2 Initial	8.167	8.138	8.132	8.133	8.138	8.138	8.138	8.162	8.143	0.013
Final		8.094	8.128	8.133	8.148	8.148	8.146	8.163	8.137	0.021
Difference		0.044	0.004	0.000	-0.010	-0.010	-0.008	-0.001	0.006	
3 Initial	8.156	8.130	8.127	8.125	8.132	8.126	8.130	8.155	8.135	0.012
Final		8.070	8.113	8.113	8.127	8.136	8.137	8.148	8.129	0.024
Difference		0.060	0.014	0.012	0.005	-0.010	-0.007	0.007	0.006	
4 Initial	8.159	8.131	8.128	8.127	8.132	8.126	8.131	8.155	8.136	0.012
Final		8.071	8.114	8.115	8.129	8.136	8.138	8.149	8.130	0.024
Difference		0.060	0.014	0.012	0.003	-0.010	-0.007	0.006	0.006	
5 Initial	8.168	8.148	8.146	8.143	8.148	8.146	8.146	8.164	8.151	0.009
Final		8.096	8.130	8.133	8.143	8.143	8.150	8.157	8.136	0.018
Difference		0.052	0.016	0.010	0.005	0.003	-0.004	0.007	0.015	
6 Initial	8.190	8.179	8.183	8.180	8.183	8.179	8.178	8.186	8.182	0.004
Final		8.155	8.174	8.177	8.178	8.182	8.182	8.180	8.175	0.009
Difference		0.024	0.009	0.003	0.005	-0.003	-0.004	0.006	0.007	
7 Initial	8.194	8.171	8.164	8.171	8.173	8.178	8.164	8.191	8.176	0.011
Final		8.138	8.162	8.162	8.168	8.179	8.175	8.187	8.167	0.015
Difference		0.033	0.002	0.009	0.005	-0.001	-0.011	0.004	0.008	
8 Initial	8.180	8.148	8.150	8.150	8.151	8.156	8.151	8.178	8.158	0.012
Final		8.103	8.134	8.136	8.146	8.157	8.149	8.167	8.142	0.019
Difference		0.045	0.016	0.014	0.005	-0.001	0.002	0.011	0.016	
9 Initial	8.175	8.166	8.147	8.145	8.146	8.150	8.144	8.173	8.156	0.012
Final		8.079	8.122	8.124	8.137	8.150	8.149	8.160	8.132	0.025
Difference		0.087	0.025	0.021	0.009	0.000	-0.005	0.013	0.024	
10 Initial	8.175	8.166	8.148	8.146	8.146	8.150	8.144	8.172	8.156	0.012
Final		8.080	8.122	8.125	8.138	8.150	8.146	8.160	8.132	0.024
Difference		0.086	0.026	0.021	0.008	0.000	-0.002	0.012	0.024	
11 Initial	8.185	8.153	8.163	8.163	8.161	8.163	8.160	8.183	8.166	0.011
Final		8.107	8.141	8.145	8.146	8.159	8.157	8.168	8.146	0.018
Difference		0.046	0.022	0.018	0.015	0.004	0.003	0.015	0.020	
12 Initial	8.206	8.186	8.196	8.193	8.191	8.192	8.191	8.203	8.195	0.006
Final		8.164	8.181	8.184	8.182	8.184	8.187	8.189	8.182	0.008
Difference		0.022	0.015	0.009	0.009	0.008	0.004	0.014	0.013	
13 Initial	8.207	8.183	8.183	8.188	8.190	8.194	8.185	8.203	8.192	0.009
Final		8.138	8.160	8.164	8.171	8.182	8.171	8.189	8.168	0.015
Difference		0.045	0.023	0.024	0.019	0.012	0.014	0.014	0.024	
14 Initial	8.192	8.163	8.168	8.173	8.170	8.178	8.166	8.193	8.175	0.011
Final		8.108	8.143	8.143	8.153	8.166	8.151	8.182	8.149	0.021
Difference		0.055	0.025	0.030	0.017	0.012	0.015	0.011	0.026	
15 Initial	8.191	8.152	8.166	8.170	8.163	8.173	8.161	8.192	8.171	0.013
Final		8.093	8.135	8.137	8.143	8.161	8.150	8.181	8.143	0.025
Difference		0.059	0.031	0.033	0.020	0.012	0.011	0.011	0.028	
16 Initial	8.193	8.154	8.168	8.170	8.163	8.173	8.162	8.193	8.172	0.013
Final		8.093	8.136	8.137	8.139	8.161	8.153	8.182	8.143	0.025
Difference		0.061	0.032	0.033	0.024	0.012	0.009	0.011	0.029	
17 Initial	8.204	8.170	8.184	8.185	8.176	8.186	8.178	8.204	8.186	0.012
Final		8.118	8.156	8.162	8.140	8.171	8.162	8.178	8.155	0.019
Difference		0.052	0.028	0.023	0.036	0.015	0.016	0.026	0.031	
18 Initial	8.221	8.198	8.213	8.208	8.192	8.208	8.204	8.219	8.208	0.009
Final		8.171	8.188	8.189	8.186	8.192	8.188	8.197	8.187	0.007
Difference		0.027	0.025	0.019	0.006	0.016	0.016	0.022	0.021	
Init.Mean	8.186	8.161	8.162	8.162	8.162	8.166	8.161	8.184		
Std. Dev.	0.017	0.019	0.024	0.024	0.020	0.023	0.021	0.018		
Final Mean	0.000	8.117	8.144	8.147	8.152	8.163	8.159	8.174	8.151	0.017
Std. Dev.	0.000	0.029	0.022	0.022	0.018	0.017	0.016	0.015	0.018	0.006
Initial-Final Mean		0.044	0.018	0.015	0.010	0.003	0.002	0.010		

TABLE B.4 - Radius Measurements - Trailing Brake (inches)

Lining Position	Set 01	Set 02	Set 03	Set 04	Set 07	Set 08	Set 09	Set 10	Mean	Std. Dev.
1 Initial	8.153	8.185	8.169	8.185	8.183	8.178	8.181	8.145	8.172	0.014
Final		8.125	8.141	8.149	8.163	8.165	8.167	8.138	8.150	0.015
Difference		0.060	0.028	0.036	0.020	0.013	0.014	0.007	0.023	
2 Initial	8.134	8.166	8.159	8.186	8.176	8.158	8.162	8.121	8.158	0.020
Final		8.113	8.137	8.145	8.162	8.161	8.168	8.125	8.144	0.019
Difference		0.053	0.022	0.041	0.014	-0.003	-0.006	-0.004	0.013	
3 Initial	8.126	8.156	8.158	8.156	8.158	8.150	8.155	8.118	8.147	0.015
Final		8.114	8.141	8.146	8.163	8.163	8.166	8.124	8.145	0.019
Difference		0.042	0.017	0.010	-0.005	-0.013	-0.011	-0.006	0.002	
4 Initial	8.127	8.156	8.159	8.156	8.158	8.150	8.156	8.124	8.148	0.013
Final		8.122	8.142	8.150	8.166	8.165	8.166	8.126	8.148	0.017
Difference		0.034	0.017	0.006	-0.008	-0.015	-0.010	-0.002	0.000	
5 Initial	8.148	8.167	8.168	8.189	8.168	8.161	8.167	8.143	8.164	0.013
Final		8.148	8.166	8.166	8.169	8.170	8.174	8.143	8.162	0.011
Difference		0.019	0.002	0.023	-0.001	-0.009	-0.007	0.000	0.002	
6 Initial	8.172	8.187	8.195	8.185	8.188	8.185	8.190	8.178	8.185	0.007
Final		8.187	8.200	8.198	8.195	8.193	8.198	8.179	8.193	0.007
Difference		0.000	-0.005	-0.013	-0.007	-0.008	-0.008	-0.001	-0.008	
7 Initial	8.166	8.205	8.186	8.190	8.198	8.191	8.190	8.164	8.186	0.013
Final		8.122	8.153	8.153	8.173	8.174	8.174	8.153	8.157	0.017
Difference		0.083	0.033	0.037	0.025	0.017	0.016	0.011	0.029	
8 Initial	8.147	8.187	8.173	8.175	8.181	8.175	8.175	8.145	8.170	0.014
Final		8.110	8.149	8.150	8.172	8.173	8.174	8.142	8.153	0.021
Difference		0.077	0.024	0.025	0.009	0.002	0.001	0.003	0.017	
9 Initial	8.143	8.173	8.171	8.169	8.174	8.167	8.170	8.143	8.164	0.012
Final		8.115	8.153	8.152	8.172	8.176	8.175	8.141	8.155	0.020
Difference		0.058	0.018	0.017	0.002	-0.009	-0.005	0.002	0.009	
10 Initial	8.144	8.173	8.172	8.169	8.173	8.168	8.172	8.143	8.164	0.012
Final		8.121	8.158	8.152	8.171	8.177	8.178	8.140	8.157	0.019
Difference		0.052	0.014	0.017	0.002	-0.009	-0.006	0.003	0.008	
11 Initial	8.161	8.183	8.183	8.179	8.180	8.179	8.183	8.161	8.176	0.009
Final		8.151	8.176	8.178	8.180	8.182	8.185	8.158	8.173	0.012
Difference		0.032	0.007	0.001	0.000	-0.003	-0.002	0.003	0.003	
12 Initial	8.196	8.202	8.204	8.199	8.198	8.199	8.203	8.191	8.199	0.004
Final		8.196	8.207	8.206	8.201	8.205	8.208	8.202	8.204	0.004
Difference		0.006	-0.003	-0.007	-0.003	-0.006	-0.005	-0.011	-0.005	
13 Initial	8.183	8.205	8.207	8.197	8.212	8.217	8.201	8.187	8.201	0.011
Final		8.121	8.166	8.158	8.182	8.186	8.179	8.168	8.166	0.020
Difference		0.084	0.041	0.039	0.030	0.031	0.022	0.019	0.035	
14 Initial	8.169	8.195	8.197	8.189	8.198	8.196	8.190	8.173	8.188	0.011
Final		8.108	8.163	8.155	8.188	8.186	8.176	8.157	8.162	0.025
Difference		0.087	0.034	0.034	0.010	0.010	0.014	0.016	0.027	
15 Initial	8.168	8.193	8.195	8.189	8.192	8.194	8.189	8.171	8.186	0.010
Final		8.116	8.167	8.158	8.189	8.185	8.181	8.157	8.165	0.023
Difference		0.077	0.028	0.031	0.003	0.009	0.008	0.014	0.022	
16 Initial	8.169	8.193	8.194	8.189	8.191	8.195	8.190	8.170	8.186	0.010
Final		8.126	8.171	8.160	8.190	8.187	8.183	8.159	8.168	0.021
Difference		0.067	0.023	0.029	0.001	0.008	0.007	0.011	0.018	
17 Initial	8.184	8.203	8.201	8.201	8.194	8.202	8.197	8.184	8.195	0.007
Final		8.157	8.186	8.186	8.192	8.187	8.191	8.172	8.182	0.012
Difference		0.046	0.015	0.015	0.002	0.015	0.006	0.012	0.014	
18 Initial	8.210	8.219	8.215	8.221	8.208	8.218	8.219	8.208	8.215	0.005
Final		8.206	8.213	8.215	8.205	8.214	8.214	8.198	8.209	0.006
Difference		0.013	0.002	0.006	0.003	0.004	0.005	0.010	0.005	
Init.Mean	8.161	8.186	8.184	8.185	8.185	8.182	8.130	8.159		
Std. Dev.	0.023	0.018	0.018	0.016	0.015	0.021	0.017	0.026		
Final Mean	0.000	8.137	8.166	8.165	8.180	8.181	8.181	8.155	8.166	0.016
Std. Dev.	0.000	0.030	0.022	0.021	0.013	0.014	0.013	0.022	0.019	0.006
Initial-Final Mean		0.049	0.018	0.020	0.005	0.001	-0.051	0.004		

APPENDIX C
Alternate Text Descriptions of Figures

Figure 1.1 - Brake Effectiveness Results for Single Fixture Round-Robin

This vertical bar graph compares the results of effectiveness tests run on nine independent inertia dynamometers throughout industry. Each laboratory in rotation tested the same single fixture, lining set, and drum. The alphanumeric labels on the x-axis indicate the code for the respective laboratory and the order of repetition if the fixture was tested more than once. Below the figure is a table of letters (ranging from A to I) with correlating laboratory names. On the left y-axis, the effectiveness numbers range from zero (at the bottom) to ten (at the top). For each of the 19 bars plotted, the effectiveness value is listed at the top of the corresponding bar.

Figure 1.2 - Brake Effectiveness Ratings for Round-Robin Using Different Fixtures

This three-dimensional vertical bar graph compares the results of effectiveness tests run on three different lining types. On the x-axis, there are three bar groupings, separated by lining manufacturer type. Each type grouping is divided into 5 to 7 smaller groups corresponding to the number of laboratories that tested each type. These sub-groups are further divided to reflect the results of three sets of linings tested by each laboratory. No laboratory names are presented, but the results indicate quite a difference in measured effectiveness between laboratories and within lining types for a given laboratory. On the left y-axis, the effectiveness numbers range from zero (at the bottom) to 25 (at the top). For the depth of the array of bars graphed, the front plane of bars represents the "Normal" temperature effectiveness values, and the rear plane of bars represents the "High" temperature effectiveness values. Magnitudes of effectiveness for the first group (Abex 1083-49) range from 10 to 22. For the second group (BSI 2015), 6 to 10. For the third group (Carlisle NAB 9ML), 8 to 12. The magnitudes of effectiveness for the "High" temperature tests ranged 10 to 20 % higher than for the "Normal" temperature tests.

Figure 1.3 - Preliminary Tests of NHTSA Replacement Lining Rating Procedure

This vertical bar graph compares the variability in effectiveness for ten repetitions of effectiveness tests run on a single lining material on the VRTC inertia dynamometer. The effectiveness values are listed at the top of each corresponding bar. The bars are grouped in ten pairs, with the left bar (darker shading) representing "Normal" temperature effectiveness measurements, and the right bar (lighter shading) representing "High" temperature effectiveness measurements. The alphanumeric labels on the x-axis indicate the code for the respective lining and drum sets. On the left y-axis, the effectiveness numbers range from zero (at the bottom) to twelve (at the top).

***** - The plotting format used for Figure 1.3 was also used for the next three figures:

Figure 1.4 - NHTSA Lining Test Results for OEM Carlisle E145A/R202

Similar in format as Figure 1.3, this vertical bar graph shows the effectiveness values for five sets of OEM Carlisle E145A/R202 linings.

Figure 1.5 - NHTSA Rating Test Results for Ferodo 867 Replacement Lining

Similar in format as Figure 1.3, this vertical bar graph shows the effectiveness values for five sets of Ferodo 867 replacement linings.

Figure 1.6 - NHTSA Rating Test Results for Abex 685 Replacement Lining

Similar in format as Figure 1.3, this vertical bar graph shows the effectiveness values for five sets of Abex 685 replacement linings.

Figure 3.1 - Cam Dimensions

This figure shows the cam end view of a typical "Q-type" brake S-Cam. The drawing shows generic measurement locations on the lobes of the cam that indicate the lobe rate of rise for a given input angle variation. Theta is the cam rotation angle. A-0 is the initial cam height at angle zero (typically half of 1.121 inches, the thickness of the starting point on the cam). A-theta is the cam height at angle theta. The rise rate is the difference between A-theta and A-0, divided by the rotation angle theta. The two-lobed cam itself is symmetrical about the centerline of the camshaft axis when rotated 180 degrees.

Figure 3.2 - VRTC Cam Profiler

This figure is a photograph of the VRTC-built cam profiler. The system consists of a flat steel plate with a guide track milled down the length at the center. Several fixtures mount onto the track. From the right end is a metal block that holds the vertical frame where a 4-inch linear potentiometer is affixed with steel band clamps. The orientation of the "pot" is vertical and centered over the track, with the piston pushrod protruding from the bottom. A 1-inch, hard rubber, narrow roller (follower) wheel and fork assembly are attached to the bottom end of the pushrod. The axis of the follower is oriented parallel to the track so it will roll freely when the lobes of a test cam are positioned below it. A suitable steering arm and vertical slider assembly are attached to the fork to maintain the correct axial orientation of the follower. At mid-span and near the left end of the base plate are two pillow blocks These blocks are mounted on the centerline of the track and a test camshaft passes through them and parallel to the track. The S-Cam assembly is oriented with the lobes on the end to the right, and placed under the roller for lobe height measurement. At the left end of the plate is a fourth block that mounts the rotary potentiometer for cam angle input measurement. The "rotary pot" is oriented so the axial centerline matches the axial centerline of the splined end of the camshaft. The two are coupled with a magnet attached to the "rotary pot". Both pots connect to a data system for collecting data.

Figure 3.3 - Brake Spider

This figure is a simplified sketch of a typical S-Cam "spider" casting. It is a large round casting with somewhat raised sides. A large hole is cut in the center through which the axle passes. Around the axle opening are 16 equally spaced bolt holes used to mount this component onto the axle flange. There are two extended areas on the spider at opposite sides. One has an area to hold the two anchor pins, the other the area to pass through the camshaft.

Figure 3.4 - United Test System for Calibrating Brake Chamber

This figure is a photograph of the system used to calibrate brake chambers. The basic system is a United brand 30,000 pound universal test machine with a vertical measuring orientation. A test chamber is fitted into a small metal frame. The frame rests on the table of the tensile machine. The chamber pushrod protrudes vertically upward and is free to extend through a hole in the small frame. The load cell is suspended from the top mandrel and lowered to rest on the pushrod. Air is applied to the chamber and the test machine measures the force and displacement.

Figure 3.5 - Typical Measurements in a Chamber Calibration File

This graph contains three plots, all plotted against time on the x-axis. The first plot (near the top of the graph) shows a control pressure maintained at 80 psi until the pushrod nears the end of its travel. The middle plot shows the load force beginning around 2400 pounds and drooping to 2200 pounds as the pushrod moves outward from zero to 2.8 inches. Then the load force drops sharply to zero as the load cell is withdrawn above the maximum extended length of the pushrod. The lower plot shows the linear extension of the pushrod as the load cell is withdrawn from the chamber.

Figure 3.6 - Typical Curve of Chamber Pressure vs. Pushrod Stroke

This graph shows the pressure vs. stroke correlation between the raw data and the interpolated values. The two curves are nearly indistinguishable from the other. Between 0.5 inches and 2.8 inches of stroke, the pressure is nearly constant at 100 psi. The typical range of stroke encountered for effectiveness tests is highlighted as 1 inch to 1.8 inches.

Figure 3.7 - Repeatability of Two Calibration Tests, Force as a Function of Time

This graph is similar to the middle plot on Figure 3.5. Here, there are two overlaying plots representing the high level of repeatability of successive pressure applications of a chamber. The plot shows the two plots starting near 3000 pounds at 5 seconds and drooping to 2800 pounds at 35 seconds, where the chamber bottoms out and the force drops sharply to zero. There is no distinguishable difference between the plots.

Figure 3.8 - Repeatability of Two Calibration Tests, Force as a Function of Stroke

This graph uses the data from Figure 3.7 and re-plots with force vs. pushrod stroke. The shape of the curve is similar in appearance to that in Figure 3.7, except that for the x-axis, the stroke ranges from 0.3 to 2.8 inches. Again, there is no distinguishable difference between the plots.

Figure 3.9 - Chamber Calibration Raw Data and Interpolated Values

This graph is similar in layout to Figure 3.8, only the raw data is compared to interpolated data. The interpolation procedure is described in the text on page 24.

Figure 3.10 - Plot of Typical Service Chamber Lookup Table

This graph is similar in layout to Figure 3.8, except that 20 plots are presented. There are two plots for each pressure level input and repetitions for 10 pressure levels. This family of curves duplicates the appearance of the plots in Figure 3.8 that used just one pressure input. Here, the different pressure levels are graduated downward in nearly linear increments for the relatively flat region while the stroke ranged from 0.5 inches to 2.8 inches.

Figure 3.11 - Cam Profile Data From J1802

This figure contains a data table and graph of data for s typical J-1802-type S-Cam. The graph shows the Cam rotation, in degrees, rising from zero to 150 degrees on the x-axis. For the y-axis, the resulting cam displacement linearly rises from 1.186 inches to 2.512 inches.

***** - The plotting format used for Figure 3.10 was also used for the next four figures:

Figure 3.12 - Lookup Table Values for Abex Service Chamber

This graph shows the force vs. stroke results for the Abex service chamber. They appear similar to the plots in Figure 3.10.

Figure 3.13 - Lookup Table Values for Carlisle Service Chamber

This graph shows the force vs. stroke results for the Carlisle service chamber. They appear similar to the plots in Figure 3.10.

Figure 3.14 - Lookup Table Values for VRTC Service Chamber

This graph shows the force vs. stroke results for the VRTC service chamber. They appear similar to the plots in Figure 3.10.

Figure 3.15 - Overlay of Lookup Table Values for all Service Chambers used in this Study

This graph shows the force vs. stroke results overlaid for all three service chambers. They appear similar to the plots in Figure 3.10. The outputs are nearly the same for the linear stroke range of 1 to 2 inches.

Figure 4.1 - Greening Inertia Brake Dynamometer

This figure is a photograph of the VRTC dynamometer system. See description in Section 4.2.3 on page 37.

Figure 4.2 - Drum and Shoe Assemblies

This figure is a photograph of a typical J1802 lining set and drum. The Webb drum is 16.5-inch diameter by 7 inch wide. The linings (from Brake Pro) are mounted on cast shoes and have not yet been ground to the J1802 test specification for this test series.

Figure 4.3 - Required SAE J1802 Radius of Curvature

This figure is a reproduction of the detail specified in the SAE Recommended Practice J-1802, see Reference No. 1.

Figure 4.4 - VRTC Lining Radius Fixture

This figure is a photograph of the VRTC Lining Radius Fixture used to measure the brake block outside radius after being ground to the initial radius used for this test series. The fixture includes a pin and roller adapter to correctly mount the shoe on its side for repeatable measurements. The fixture includes a shoe mount and swivel arm. The swivel arm is free to swing through an arc of 360 degrees. The cantilevered arm loops over the shoe to the outside and hold a dial indicator. The dial indicator faces upward (for ease of operator use), with the penetrator pointing radially inward to measure the outside radius on the mounted test shoe and lining. The swivel arm can also be displaced vertically to allow for multiple measurements laterally across the face of the brake blocks.

Figure 4.5 - Radius Locations on Each Shoe

This figure shows the indexing points used for both the leading and trailing shoes when measuring the lining radius. The top sketch shows the leading shoe and the bottom sketch shows the trailing shoe. Both sketches are flattened representations of the shoes when viewed radially from the center of the two brake blocks. Both views show the cam end of the shoe on the left and the anchor end on the right. Each shoe was measured at 18 locations. Numbers on the sketches indicate the respective positions (as listed in Tables 4.2 and 4.3). There are 6 columns of numbers in 3 rows, beginning with 1 in the upper left and ending with 18 on the lower right. The measurement location columns were 1-1/2 inches from each end of each block and centered at mid-span. The rows were 1-1/2 inches in from each of the sides and one in the center.

Figure 4.6 - Thickness Measurement Locations on Each Shoe

This figure shows the indexing points used for both the leading and trailing shoes when measuring the lining thickness. The top sketch shows the leading shoe and the bottom sketch shows the trailing shoe. Both sketches are flattened representations of the shoes when viewed radially from the center of the two brake blocks. Both views show the cam end of the shoe on the left and the anchor end on the right. Each lining was measured at 12 locations. Numbers on the sketches indicate the respective positions (as listed in Tables B1). There are 6 columns of numbers in 2 rows, beginning with 1 in the upper left and ending with 12 on the lower right. The measurement locations were similar to the Figure 4.5 Radius Locations, except there were no circumferential center row of measurements due to interference between the web of the shoe and the measuring tool. Only the side measurements were made here.

Figure 4.7 - Brake Installation on Dynamometer

This figure is a photograph of a typical J1802 S-Cam brake installation on the VRTC dynamometer. The top of the tunnel (cooling air duct) has been removed for ease of viewing the brake assembly. In the center of the picture is the drum of the left wheel assembly. The foundation brake hardware is to the right with the chamber mounted nearly vertically and to the far side of the drive shaft. The cam was oriented to apply the brake when rotating in the same direction as the wheel when traveling forward. Further to the right is the pedestal containing the torque load cell. To the left of the drum are the “wheel” adapter tube, drive pin assembly, and slip-ring array used to measure the drum temperatures.

Figure 4.8 - Normal Temperature Effectiveness - VRTC Test Fixture - Lining Conditioning Tests

This vertical bar graph shows 9 bars representing the various lining sets tested. The first five bars correspond to Brake Pro linings and the other four bars to Haldex/Midland linings. The y-axis is scaled from 0 to 10 in level of effectiveness. The magnitude of each bar is listed at the top of each bar. They ranged from 7.2 to 9.2 for the first group and from 5.9 to 6.9 for the other group.

Figure 4.9 - High Temperature Effectiveness - VRTC Test Fixture – Lining Conditioning Tests

This vertical bar graph is similar to Figure 4.8 and shows 9 bars representing the various lining sets tested. The first five bars are for Brake Pro linings and the other four bars are for Haldex/Midland linings. The y-axis is scaled from 0 to 10 in level of effectiveness. The magnitude of each bar is listed at the top of each bar. At this “high temperature” level, the effectiveness values ranged from 6.2 to 7.9 for the first group and from 4.9 to 5.3 for the other group.

***** - The plotting format used for the next 8 figures (Figures 4.10 to 4.17) is similar. Each is a graph of lining effectiveness, or output torque (on the ordinate) vs. input torque (on the abscissa). The x-axis is scaled from 1,000 to 10,000 pound-inches and the y-axis is scaled from 10,000 to 80,000 pound-inches of torque. The first four figures show plots where the data is presented for a single brake set, but tested on two different fixtures. The other four figures show plots where two different linings from a single type group were compared for a single fixture. For regression formulas listed on each graph, the first letter of the name code stands for the fixture supplier: A for Abex, C for Carlisle. The second and third characters stand for the brake block supplier: BP for BrakePro, HM for Haldex/Midland. The final two characters (numbers) stand for the lining set numbers: 03, 04, 07, & 10.

Figure 4.10 - BrakePro 03 Lining Effectiveness Values for the Abex and Carlisle Fixtures

Regression slopes are: ABP03 = 8.094, CBP03 = 7.946

Figure 4.11 - BrakePro 04 Lining Effectiveness Values for the Abex and Carlisle Fixtures

Regression slopes are: ABP04 = 7.861, CBP04 = 8.070

Figure 4.12 - Haldex 07 Lining Effectiveness Values for the Abex and Carlisle Fixtures

Regression slopes are: AHM07 = 6.512, CHM07 = 7.163

Figure 4.13 - Haldex 10 Lining Effectiveness Values for the Abex and Carlisle Fixtures

Regression slopes are: AHM10 = 7.703, CHM10 = 7.806

Figure 4.14 - BrakePro Lining Effectiveness Values for the Abex Fixture

Regression slopes are: ABP03 = 8.094, ABP04 = 7.861

Figure 4.15 - BrakePro Lining Effectiveness Values for the Carlisle Fixture

Regression slopes are: CBP03 = 7.946, CBP04 = 8.070

Figure 4.16 - Haldex Lining Effectiveness Values for the Abex Fixture

Regression slopes are: AHM07 = 6.512, AHM10 = 7.703

Figure 4.17 - Haldex Lining Effectiveness Values for the Carlisle Fixture

Regression slopes are: CHM07 = 7.163, CHM10 = 7.806

Figure 4.18 - Normal Temperature Effectiveness Values of All Conditioning and Test Runs

This vertical bar graph is similar to Figure 4.8 and shows 9 groups of bars representing the various lining sets tested. Each group of bars consists of 1 to 3 individual bars representing the text fixture used (VRTC, Carlisle, and Abex, respectively). The first five groups of bars are BrakePro linings and the other four groups of bars are Haldex/Midland linings. The y-axis is scaled from 0 to 10 in level of effectiveness. The magnitude of each bar is listed at the top of each bar.

***** - The plotting format used for the next 4 figures (Figures 4.19 to 4.22) is similar to the previous group: Figures 4.10 to 4.17, whose notes began at the bottom of page 98. Again, each is a graph of lining effectiveness, or output torque vs. input torque. The x-axis is scaled from 1,000 to 10,000 pound-inches and the y-axis is scaled from 10,000 to 80,000 pound-inches of torque. For this group, all four figures show plots where the measured input cam torque is compared to the calculated input torque using data from the chamber calibrations and both stroke and pressure measurements. The same lining and fixture coding structure is used as done previously. Only the Abex fixture was equipped with a strain gage on the shaft of the S-Cam.

Figure 4.19 - Comparison of Measured and Calculated Input Torque - BrakePro 03

Regression slopes for ABP03 are: Cam Torque = 8.645, Calculated Torque = 8.094

Figure 4.20 - Comparison of Measured and Calculated Input Torque - BrakePro 04

Regression slopes for ABP04 are: Cam Torque = 8.508, Calculated Torque = 7.861

Figure 4.21 - Comparison of Measured and Calculated Input Torque - Haldex 07

Regression slopes for AHM07 are: Cam Torque = 7.221, Calculated Torque = 6.512

Figure 4.22 - Comparison of Measured and Calculated Input Torque - Haldex 10

Regression slopes for AHM10 are: Cam Torque = 8.397, Calculated Torque = 7.703